Columbia University
PALISADES, NEW YORK

Lamont Geological Observatory

Technical Reports on Seismology

No. 12

Studies of Frontal, Cyclonic and Hurricane Microseisms Generated in the Western North Atlantic

Part II - Cyclonic Microseisms

Lamont Geological Observatory

(Columbia University)

Palisades, New York

STUDIES OF FRONTAL, CYCLONIC AND HURRICANE MICROSEISMS GENERATED IN THE WESTERN NORTH ATLANTIC

PART II - CYCLONIC MICROSEISMS

Technical Report No. 12

by

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The research reported in this document has been made possible through support and sponsorship extended by the Geophysical Research Directorate of the Cambridge Field Station, AMC, U.S. Air Force, under Contract AF-19(122)441 Dept. 554. It is published for technical information only and does not represent recommendations or conclusions of the sponsoring agency.

March 1951

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PART II - CYCLONIC MICROSEISMS

CONTENTS

ABSTRACT

Nearly all of the microseism storms generated by fronts, extra-tropical cyclones and hurricanes in the western North Atlantic during the Fall and Winter seasons of 1948-49 and 1949-50 have been studied, together with some storms that occurred during the 1950-51 Fall-Winter. Seismograms from a large number of stations along the eastern and Gulf coasts of United States and the West Indies and Bermuda were examined for each storm.

Each of the microseism storms have been correlated with a particular marine atmospheric disturbance. The period of the microseisms generated appears to be a function of the depth of water in the generating area, and the regularity of the microseisms is a function of the uniformity of depth in the generating area. The effect of distance between the generating area and the station appears to be a selective one owing to more rapid decay of short-period microseisms. As a consequence of the above empirical generalizations, the position and nature of marine disturbance can often be estimated from the nature of the recorded microseisms.

All the evidence on origin tends to negate ocean swell, standing waves produced by interference of ocean swell, and surf as mechanisms producing the observed microseisms. The study suggests atmospheric pulsations resulting from turbulence, or instability to be at the root of microseism origin.

Anomalies of propagation of hurricane microseisms suggest the existence of a zone or surface of discontinuity along at least a portion of the outer margin of the east-coast continental shelf.

ACKNOWLEDGEMENTS

Professor Maurice Ewing of Columbia University was the sponsor of the research program and extended invaluable advice during the research and manuscript preparation. Necessary funds were supplied from Contract AF-19 (122)-441 between Columbia University and the United States Air Force. Dr. Frank Press, director of the above contract, read and criticized the entire manuscript.

A number of people were of great assistance in their co-operation through furnishing seismograms covering many long intervals. Marion H. Gilmore, Geophysicist at the United States Navy Hurricane Weather Central, Miami, Florida supplied records of the Navy Hurricane Tracking Seismograph Stations in and around the Gulf of Mexico and Caribbean Sea. Father Daniel Linehan, S.J. and Mr. V. John Mankiewicz made available a six months continuity of records from the Weston College observatory. Seismograms and other information were generously furnished by Father J. Joseph Lynch, S.J. and Dr. William Lynch of Fordham University. The United States Coast Geodetic Survey, and in particular Dr. Leonard Murphy, were very helpful in supplying records from the seismograph stations on Bermuda and San Juan, P.R. Copies of records from the Azores were transmitted by Prof. A. Ferrieoa at Largo de Santa Isabel. Dr. W. G. Milne of the Dominion Observatory in Ottawa, Canada made available records from Halifax.

In addition to the seismograms, marine weather charts were essential for the study. The chief source of this weather data has been the Ocean Forecast Section of the United States

Weather Bureau, at La Guardia Field on Long Island. They have supplied continuously for several years, four of each of the six-hourly North Atlantic synoptic surface charts. Mr. W. D. Boehner has been especially coöperative. Supplementary weather data necessary in critical instances was also obtained in many cases from the Air Weather Service at Andrews Air Force Base in Washington, D.C. and from the WBAN Analysis Center at the U.S. Weather Bureau, also in Washington, D.C.

Assistance, particularly in the performance of measurements on the seismograms was given by Alan Vestrich, Maurice Rosen, and Robert Katz, all senior students in geology and physics at Brooklyn College.

INTRODUCTION TO PART II

Part II of this study treats of microseism storms that have been generated by marine low pressure areas or cyclones - more technically, "extra-tropical cyclones". Only cases in which the origin of the microseisms could be uniquely attributed to one low pressure system have been considered. In Part I of this study, on Frontal Microseisms, generation of recorded microseisms was restricted to small distances from the recording stations. This was essentially the result of the limited area of generation associated with fronts. The size and intensity of the cyclones considered here have permitted the recording of measurable microseisms at stations near New York City that were generated by marine storms beyond the southern coast of Greenland. As a result a greater diversity of environmental conditions affecting the origin and propagation of microseisms could be studied.

Again a series of case histories is given for both a single station and several stations. The case histories for the single station utilize the original short-period (see Part I) and the long-period seismograph records made from September 1 to December 31, 1949 at the Palisades station of the Lamont Geological Observatory (Columbia University). The case histories of microseism storms recorded simultaneously at several stations compare the records of Bermuda (U.S. Coast and Geodetic Survey, Milne-Shaw), Fordham (Galitz n, Weston (long-period Benioff) and Halifax (Mainka) from September 1 to December 31, 1948. The records for each day for this

entire interval were examined for each of these stations except Halifax.

During the above interval in 1948, 25 cyclones of significance moved across the ocean area in which measurable microseism generation was possible. The intensity of the microseism storms that resulted varied with the area and intensity of the cyclones. The case histories of seven fairly intense microseism storms are presented here, and the results shown are typical of the greater number studied. During 1949 for the interval under consideration, 26 significant cyclones traversed the area and the case histories given are typical of all.

In addition, the microseism storm resulting from one middle latitude hurricane in 1950 is given since the resulting data and conclusions help complete the picture given by the cyclonic studies. This is followed by a discussion of amplitude, period, and regularity of microseisms based on the data of the cases presented.

Explanations of procedures of study and of illustrative data have been given in Part I (10) of this report, however a re-listing of the seismograph station symbols used on the charts is repeated for convenience.

B - Bermuda (U.S. Coast and Geodetic Survey and Navy Hurricane Tracking Stations)
C - Columbia University
New York City Station in 1948
Palisades, N.Y. Station in 1949 and 1950
CP - Cherry Point
F - Fordham University
H - Halifax, Nova Scotia
W - Weston College Observatory

Note that the Halifax and Cherry Point stations are new in the listing. Records were obtained from these stations toward the end of the study to check certain findings based on the studies of the original stations. The present Palisades station of Columbia University is about 12 miles north of the symbol "C", which marks the approximate position in 1948. The former station rests on Palisades diabase whereas the latter was on Manhattan schist.

CASE HISTORIES OF CYCLONIC MICROSEISM STORMS

1. Microseism Storm - October 25 to 29, 1949.

The microseismic and associated meteorological conditions for October 25 to 29, 1949 are shown in Figures 1 and 2, respectively. Figure 1 shows portions of the Palisades long- and short-period seismograms at intervals such as to present a good sample of the records for the entire time. About two minutes of each line are presented. The measured values for double trace amplitude and period are shown on the graph.

Three successive twenty-four hourly weather maps in Figure 2 trace the path and development of the cyclone or low responsible for the microseism storm. Chart A for 1230, October 26 shows a small storm centered northeast of Long Island with its cold front extending southwestward just off the eastern tip of the island. During the following twenty-four hours the storm intensified rapidly and grew in size as the center moved northeastward to a position just north of Newfoundland, as illustrated on Chart B. Intensification and growth of the storm continued, as seen on Chart C, again twenty-four hours later, at which time the cyclone was centered just south of Greenland, with observed winds of force 8 prevailing over large areas of deep water. The steep pressure gradient indicates that even higher velocities probably existed.

From Figure 1 it is very evident that the times of maximum response of the two instruments to the microseisms

generated by the cyclone differ noticeably. Also, the microseism period existing at the times of maximum response is very different, being 1.6 to 2.5 seconds for the short-period instrument, and 5.5 seconds for the long-period instrument. The amplitude curve for the short-period seismograph (solid line) indicates maximum microseism intensity when the cyclone was still weak and close, at about the time of chart A. The second peak at 1400, October 27 is associated with the passage of the second cold front seen on Chart B. The long-period amplitude curve (broken line) shows a similar but later peak in response to this front (this effect has been explained in Part I). Maximum long period microseism intensity was recorded when the storm was over the large expanse of deep water south of Greenland. Despite increasing distance over deep water the microseism period levelled at 5.6 seconds and then declined slightly.

A comparison of the actual traces in Fig. 1 will also be helpful. The first set for October 26 shows the commencement of the storm on the short period trace while the long-period trace is at low noise level. The second set, for October 26 shows maximum activity on the short-period trace, with the first slight indication of activity on the long-period trace. The third set (October 27) shows continued increase in intensity on the long-period trace, with the microseisms noticeably irregular. The fourth set (October 28, 05-08) shows the short-period microseisms declining, while the long-period microseisms become much stronger. By this time most of the cyclone has passed across the Newfoundland and Grand Banks shoals and over

onto deep water. The microseism storm groups on the long-period trace are strikingly regular. This indicates a lack of reception of significant short-period microseisms from the generating area, since the instrument has been shown to be capable of responding to them. On the other hand, the short-period trace is extremely irregular, with individual waves distorted from what seems to be the effect of short background microseisms superposed on longer storm microseisms. The result is to give a rectangular, castellated form to the waves. When these long distorted waves are measured, the values for period are about the same as for the regular microseisms recorded on the long-period trace. This short-period set is distinctly different from the normal background microseisms shown on the last set, for Oct. 29. This effect has always enabled, when present, the prediction of the approximate position of the generating cyclone. This phenomenon will be discussed more completely in a different paper. The fifth set (Oct. 28, 22-24) shows conditions just after maximum long period activity, and illustrates the same regularity on the long-period trace, and irregularity on the short-period trace, although the amplitude of the latter has diminished, with normal background microseisms becoming more prominent. The last set shows essentially background on both traces.

In summary, the above case compares the short- and long-period seismograms for a single station for the microseisms generated by a particular cyclone. The amplitude maximum of the short-period instrument occurs much earlier than that of the long-period instrument. The amplitudes recorded by the

long-period instrument increased as the generating cyclone receded over deepening water. After reaching a maximum, the microseism period levelled despite further increase in cyclone distance.

2. <u>Microseism Storm of November 14 to 15, 1948.</u>

The trace amplitudes and periods of microseisms recorded at the Bermuda (USC&GS), Fordham and Weston Observatories for November 14 to 15, 1948, together with portions of the Weston records and the related marine weather, are illustrated in Figures 3 and 4, respectively. Arbitrary units have been used on the amplitude coordinate in order for the three curves to be presented on a single graph.

Figure 4, A to D traces the movement and development of the cyclone responsible for the microseism storm. Chart A, 0030 Nov. 14, shows the storm shortly after it had developed over east-coastal waters of variable depths. Chart B, at 1230, shows the forward (northern) section of the storm over Newfoundland and the surrounding shoal waters. A considerable area of high winds still existed over open water to the south owing to the increased size and intensity of the storm. Chart C shows the entire central area of the cyclone over Newfoundland and surrounding shoals, with a distinct, although reduced high wind area to the south. Chart D, at 1230, Nov. 15, shows almost the entire storm over deep open water near mid-ocean to the south and southeast of Greenland.

Figure 3 presents amplitude and period values for the long-period seismographs at the Bermuda, Fordham and Weston

stations, together with abridged portions of the Weston record, in which four minutes of each line reproduced is given. Despite the different response of the above instruments, a fairly striking resemblance of the amplitude curves is evident, with two maxima being noted. The first maximum on the Bermuda curve is not very prominent. This is explained by the very low magnification of the instrument, and the low sensitivity at short periods coupled with the much longer distance of this station from the generating area. The curves for period are also in good conformance with each other.

The first amplitude maximum occurred at 1200 on November 14, when the microseism period was about 4 seconds. This was just prior to the conditions shown on Chart B, with winds of force 8 prevailing over both shoal and deep waters east of New England and south of Newfoundland. The Weston trace at about this time is shown from 0900 to 1200, Nov. 14, and exhibits a prominent irregularity resulting from the presence of microseisms covering a broad spectrum of periods.

The amplitude minima, between 1800 and 2400 on Nov. 14, correspond exactly to the time when the largest portion of the storm was over Newfoundland and surrounding shoals. This can be seen from Chart C of Figure 4.

The second and more prominent amplitude maximum on each of the curves occurred at the time when the cyclone was largely over deep ocean water south of Greenland. The amplitude rise coincides with the movement of the cyclone from the Newfoundland area to the more distant deeper water zone. Following this maximum the microseism storm diminished in intensity

owing to the increasing distance of the low pressure area. It is notable that the greatest recorded intensity of the microseism storm occurred when the cyclone was quite distant from these stations, and approximately at the time of maximum microseism period.

The last (lowermost) of the record portions reproduced shows microseisms of distinctly greater amplitude, period, and regularity than appeared at any time earlier in the storm. The trace lines from 0900 to 1200, November 15 show conditions when both amplitude and period were at maximum, and when the generating area was over remote, deep waters. It appears that the spectrum of periods received from the cyclone was initially broad and became narrower with energy shifting to the long-period end as the cyclone receded over deeper waters. The amplitude behavior further indicates that the energy in the longer period waves increased with time.

The graphic curves for microseism period resemble those for amplitude. An initial increase is followed by a flattening and then a further increase. The initial rise of the curve correlates with the early development and movement of the cyclone preceding the time of Chart A. The flat portion of the curve corresponds to the time of increasing cyclonic distance over shoaling waters. The rise to maximum corresponds to the transition of the cyclone over the larger deep water expanse east of Newfoundland. The Bermuda period curve shows some discrepancy at the long period end, compared to those of Fordham and Weston. However, the difference is actually within

the range of the reading error for the Bermuda seismograms. In considering the above seismic and meteorologic conditions, it is thus seen that the amplitude, period, and regularity of the microseism storm can be correlated with distinct positions of the generating cyclone. The unchanging periods as the cyclone receded over shoal waters, and the increase of period as the cyclone moved over deep water suggests that water depth is of fundamental importance as a factor affecting microseism period.

Subsequent to the study of the storm just described, the records from Halifax, Nova Scotia were obtained from the Dominion Observatory. This station lies about ten degrees to the northeast of Fordham and Weston, in the direction of movement of the cyclone considered here. The measured values of period and amplitude for the new records are shown in Figure 5. The curves here match very well the period and amplitude curves already described and show the same trends and variations with time, lending further support to the observations and conclusions presented above. It is noted that the first maximum on the Halifax records occurred some six or more hours subsequent to that of Fordham or Weston, but at the same short period. This is easily explained since the cyclone was traveling toward Halifax and produced highest short-period microseisms at that station when the cyclone was close to the station. However, the long-period amplitude maximum occurred at the same time as for the other stations, after the generating cyclone had cleared the Grand Banks shoals.

In summary, the above situation compares primarily the response of Bermuda, Fordham, and Weston long-period instruments to a cyclonic microseism storm. A marked amplitude decrease occurred when the generating cyclone crossed the Grand Banks shoals. Amplitudes reached a higher maximum after the cyclone passed from the shoals onto deeper water of the North Atlantic, despite increasing distance from the recording stations. The period trends at the three stations suggest that the propagation paths have little influence on microseism period which are essentially a function of conditions in the generating area. Information from the Halifax station supports the data and conclusions based on original stations studied.

3. Microseism Storms of December 11 to 24, 1948.

Four successive and distinct microseism storms occurred from December 11 to 24, 1948. The storms were studied first on the long-period seismograms of Fordham and Weston observatories, and subsequently on those of Halifax. The measured amplitude and period values for the entire interval are shown graphically in Figure 6.

The paths of the cyclonic storms associated with these microseisms are illustrated in Figure 7. The heavy lines represent the tracks of the cyclone centers with short cross-lines indicating the six-hourly positions of 0030, 0630, 1230 and 1830, GCT. The date is given with the 0030 position, and also for the first and last positions. As shown on previous illustrations the areas of such cyclones were quite large, extending for many degrees transverse to, and in the line of, the tracks at any time. Consequently the centers of the

generating areas do not correspond with the storm center points. Each of the successive cyclones originated close to (within a few degrees of) Long Island and moved generally north-eastward, crossing or just skirting the Newfoundland shoals.

A striking similarity exists between the amplitude and period curves for the Fordham and Weston instruments as exhibited in Figure 6, for the entire 13 day interval. Since the measuring of the records was accomplished by different observers at widely separated times before the information was plotted, it is believed that these curves represent very objective values. It is noticed that there are many more amplitude peaks than cyclonic storms, so that the amplitude curves in themselves would not be indicative of the number and kinds of meteorological disturbances responsible. However, the pattern is clarified by a glance at the period curves in the upper part of the figure. Four distinct trends are noticed, each with a rise to maximum followed by flattening at 6 seconds, (with the exception of storm C) and thus delineate sharply the commencement and termination of the four microseism storms. Thus, microseism storms A, B, C, and D were generated respectively by Cyclones A, B, C, and D.

A reexamination of the amplitude curves now shows that with the exception of Storm C, each microseism storm shows two peaks, and that the flattening of the period curves at maximum period very nearly coincides with the time of the second peak. Each of these nearly simultaneous effects can be

correlated with the passage of the generating cyclone onto deep water beyond Newfoundland.

Each of the troughs on the amplitude curves, between the double peaks for a particular storm correlate with the time when most of the effective wind area of the cyclone was over Newfoundland and the surrounding shoals. No decrease in the intensity of the cyclones occurred at this time. In general, an increase in area and intensity occurred. The trough in the case of Storm B is noticeably shallow and is only suggested on the Fordham curve, which exhibits a nearly continuous rise to maximum. Inspection of the path of Cyclone B-1 on Figure 7 reveals that the center track of this disturbance actually skirted the shoals in contrast to the others which passed directly across them. Consequently there was less effective wind area over shallow water which is taken as the explanation of the lesser amplitude trough. The intensity of the latter part of microseism storm B was undoubtedly affected by the later cyclone B-2.

The absence of a second peak on the amplitude curve for microseism Storm C is easily explained. First, Cyclone C began to dissipate after crossing the Newfoundland shoals. Secondly, the very large and intense Cyclone D developed over close waters at just this time, and was so great in area and intensity as to easily mask any effects from the weakening Cyclone C.

The effect of this new cyclone is clearly shown by

microseism Storm D. It seems significant that the period curve for Storm C levels at 5 seconds, compared to the 6 second flattening of the other three storms which occurred when a large part, or all of the effective wind area had moved over deep water beyond Newfoundland. In fact the 5 second maximum for Storm C corresponds in value to the first maximum on the period curve for Storm D, which occurred when the generating cyclones were over the Newfoundland shoals.

Both period curves for Storm D show a pronounced dip at the time when the generating cyclone was over land and the surrounding shallow water. Actually, a greater part of the effective wind area was either over shoals or land than is indicated by the track alone, and than occurred for the three earlier cyclones. As the low pressure area traveled over the deep water area between Newfoundland and Greenland, the period once again rose, and became constant at 6 seconds. The amplitude curves again show a distinct correspondence to storm position and environment.

It is significant to point out that Storm D was the most intense microseism storm studied thus far. It was generated by an extremely large cyclone with observed winds up to force 9. The combination of large area with the fairly high winds prevailing was responsible for the microseism intensity which for the instruments used, was much greater than microseisms of passing hurricanes with much higher winds, but with more limited area. Actually the amplitude curves for

this storm have been reduced to half of their originally plotted values relative to the other storms. Despite the obvious effect of area and velocity on microseism intensity, the effect on microseism period seems much less related. The period appears to be more a function of position and environment of the cyclone.

Subsequent to the completion of the study of this series of storms, records were obtained from the Halifax station, and amplitudes and periods were measured and plotted. The results are shown in Figure 6, superposed on the data of Fordham and Weston. The curves for amplitude and period for Halifax agree very well with those of Fordham and Weston, despite the relatively long distance between the former and latter pair of stations. The sensitivity of the Halifax seismograph is very low, accounting for the weaker response to the cyclones, particularly Cyclone C.

The above case compares the long-period data of Fordham and Weston, with the information from Halifax which was added subsequently matching almost exactly the previously obtained data. The amplitude curves for the four successive storms studied appear confused, but is quickly resolved into four distinct storms when the period curves are examined. The amplitudes for each of the storms show a decline when the generating cyclones crossed the Grand Banks region, and a second maximum when the cyclone reached more distant but deeper water. In each case the periods increased to a maximum of 5.5 to 6 seconds when the generating cyclone reached the deepest-water section of its path. The period then remained level.

4. <u>Microseism Storm of August 20 to 21, 1950.</u>

This intense microseism storm was generated by a hurricane that traveled northward just off the east coast, from tropical into middle latitudes. Owing to the sharp boundaries and relatively small area of this type of disturbance, the information gained from its study and a study of the resulting microseisms is a valuable supplement to the information derived from the study of cyclonic microseisms. A much more complete treatment of hurricane microseisms generated in tropical and middle latitudes will be given in Part III.

Figure 8 illustrates in its upper half, a graph of measured amplitude and period values of the microseisms recorded by the long-period instruments at Palisades, N.Y. and Weston, Massachusetts. Beneath this, charts A to C show three positions of the hurricane responsible for the recorded microseism storm.

It is seen on charts A and B that a cold front passed seaward across the coast as the hurricane made its closest approach. This was a very weak front as indicated by the force 1 to 2 winds associated, and the fact that it dissolved shortly after crossing over water. Consequently its influence can be considered negligible in contributing significantly to the recorded microseism storm. Further, it has been shown in Part I, that the long-period instruments utilized here have little or no response to any front in the positions illustrated.

The curve for microseism period shows a distinct decline

for both stations commencing about 00 00 on August 21. This corresponds almost exactly with the passage of the hurricane center over the shallow water of the continental shelf. This decline occurred as the amplitude was increasing giving it further significance, for normally microseism periods tend to vary in the same direction as amplitudes. The period recorded by the Palisades seismograph continued to decline as more of the storm passed over the shoal continental shelf. The Weston periods, after an initial decline, increased between 0600 and 1200 of August 21, and then after 1800, once again decreased at about the same rate as the Palisades periods. The reason for the period increase recorded by Weston is not quite clear, but may be related to the minor amplitude peak occurring at the same time. The microseisms recorded at both stations became more regular and uniform as the hurricane, while receding, passed completely over the shelf zone.

An interesting and significant observation can be made by a somewhat different treatment of the data. In Figure 8, microseism amplitudes are plotted against time and give fairly symmetrical curves. However, in Figs. 9,10,11, and 12 amplitudes are plotted on the track of the hurricane center as a function of storm position. The line thickness is proportional to microseism amplitudes generated by the hurricane at a given time and place. Hence, variations in thickness indicate variations in microseism intensity as a function of hurricane position. The 0030 positions for each day are dated on the storm path, with short dash lines normal to the path indicating the 0630, 1230

and 1830 positions.

The ratios in millimeters of line thickness to double trace amplitudes measured on the seismograms is given in the table below.

Cherry Point	1:4
Halifax	1:0.05
Palisades (Columbia Univ.)	1:1
Weston	1:1

It is evident that the hurricane accelerated in velocity as it moved northward so that the microseism amplitudes when plotted on the storm path yield a distinctly asymmetric curve. It is also evident that the microseism storm commenced quite abruptly and decayed slowly. For Weston, Palisades and Halifax, the sharp increase in intensity occurred as the hurricane crossed the one-thousand fathom line and moved over the continental shelf. Note that while the hurricane was to the southward, and within 200 to 300 miles of both Weston and Palisades, the intensity of recorded microseisms was very low. However, a much higher intensity occurred continuously while the hurricane was receding over the shelf area to a distance of more than 1,000 miles from the stations. These observations are the more anomalous since it has been shown empirically in this report, and by Gilmore (15), and theoretically by Press and Ewing (24) that the efficiency of microseism generation is greater for deep than for shoal water. Charts A, B, and C of Figure 8 show that no pronounced increase in hurricane area or intensity occurred that could reasonably account for the increased intensity after the hurricane moved northward over the shelf zone.

It is evident from the chart of Cherry Point amplitude variations (Fig. 12) that very strong microseisms were being generated at the time when little or no storm microseisms were felt at Palisades, Weston and Halifax. In fact the hurricane winds were at a maximum of 120 knots at this time.

A possible explanation for this anomalous response to the microseism storm is believed to lie in the effect of reflection, refraction, etc., of microseism energy either by the steeply sloping interface of shelf sediments or by a fault or other lithologic discontinuity in the basement in the vicinity of edge of the continental shelf. Other evidence for the existence of such a fault has been found experimentally in the seismic work of Ewing et al. (11). Basement discontinuities have been tentatively located in other areas from microseism anomalies by Gilmore (16) and Bernard (3).

The initial microseism build-up appears more gradual for the Palisades, than for the Weston seismograph. This can now be explained by the fact that between August 20-0030 and August 21-0030 the western margin of the hurricane was over part of the continental shelf a short distance to the west of the path of the center. The much closer Palisades instruments showed response to the microseisms presumably generated by that portion of the hurricane over the shelf.

Since the sharply limited small areas of hurricanes lend themselves to treatment of this type, a much more complete study of hurricane microseisms is under way, and the results will be published in Part III of this report.

In summary, the above case compares the long-period response of four stations to a middle-latitude hurricane. A

distinct decrease in microseism period occurred when the hurricane crossed onto the shallow continental shelf waters. Stations north of the shelf show an abrupt amplitude increase when the hurricane crossed the edge of the shelf suggesting the existence of a discontinuity caused possibly by the steep seaward face of the shelf sediments, or by a fault zone in the basement.

DISCUSSION

The most intense microseism storms seem to be the result of generation beneath strong cyclonic disturbances over the sea. Although the conclusions given here are essentially derived from a study of conditions in the western North Atlantic, Morelli (23) and Bernard (3) have recently made similar correlations for a number of storms in the eastern section of the ocean and Zanon (25) has noted similar relations much earlier. The effect of surf and interfering swell in the generation of the microseism storms studied seems to be negative. This conflicts with the recent studies of Bath (2) and earlier studies of Mendel (21) in which a high degree of correlation between surf and microseism storms has been found for the Scandinavian region. However, since high surf is invariably produced by winds from marine storms, correlation with the latter may still be involved. Many or all of the cyclonic disturbances considered above probably produced high surf on northern European coasts. The conclusions of many researchers that continental atmospheric storms are insignificant in microseism storm generation is further verified.

Based on the above case histories and on certain new material to be included, a discussion of the microseism parameters of amplitude, period and regularity is given, in addition to notes on the nature and origin of microseisms.

Amplitude

The amplitudes of recorded microseisms generated by cyclonic disturbances at sea depend upon several factors which are enumerated below:

1. The wind velocity in the generating area. No significant microseism storms have been observed from winds of less than force 3 to 4 (Beaufort), and those generated by winds of this threshold velocity are of slight intensity. It is of interest to note that micro-oscillations of the atmosphere of the order of 2 to 8 seconds have been observed by Macelwane and Ramirez (20) to develop with wind velocities above 8 mph., with the amplitudes of the oscillations increasing with increasing wind speed. Gherzi (12, 13) in 1923, and 1927 and Bradford in 1935 and 1936 (4,5), noted the strong possibility of relationship between atmospheric oscillations (vibrations) in marine storms and microseism generation.

2. The size of the generating area.

3. The distance of the generating area from the station.

4. The depth of water beneath the generating area.

5. The nature of the bottom and basement in the path of propagation.

6. The relation of the period of the recording seismograph and the period spectrum of the microseisms arriving at the station.

The intensity of any microseism storm is thus the result of the combined influences of these factors. There appears to be no threshold size to the generating area, since,

in addition to the data presented here, it has already been shown in Part I that narrow frontal zones over very limited stretches of water are capable of generating microseisms. Further, large cyclones with strong winds (from force 5 to 8 Beaufort) have produced the most intense microseism storms recorded by the stations considered here, despite the close passage of hurricanes with winds exceeding force 12. However, the areas of these more violent disturbances are relatively very restricted. Storms with a lesser wind velocity distributed over a large area seem to be more effective than storms with a higher velocity over a smaller area in the production of microseisms. No delicate quantitative parameters could be determined owing to uncertainty of exact storm areas and wind velocities.

The effect of water depth on microseism amplitudes must be considered in terms of the microseism period, and the tuning of the recording instruments. A meteorologic disturbance over shallow water may produce only a slight or no microseism storm on a long-period record, whereas a very intense microseism storm may be recorded simultaneously by a short-period instrument. The reverse would be true for a cyclone over deep (and distant water). The distance factor can not as yet be completely separated from depth in considering deep water cyclones since most of the stations utilized in this study either (a) have rather extensive adjacent shallow water zones, or (b) do not have both short- and long-period instruments if surrounded by deep water.

The effect of the bottom or basement in the path of propagation will be treated much more completely in Part III of this report. However, from the data presented it appears that microseism energy is dissipated by a discontinuity along the edge of the continental shelf south of New England.

Periods

The range of cyclonic microseism periods for all of the storms studied was from about 2.0 to 7 seconds. In general the periods of microseisms resulting from a particular cyclone tend to follow, in a subdued manner, the changes in amplitude providing the environments of generation and propagation remain uniform. This tendency has been noted by many investigators, particularly Bath (2), Bradford (5), Gilmore (15) and Jones (17).

A certain spectrum of periods is actually received at a given station as a result of a cyclone at sea. The narrower is this spectrum the more regular is the record of the microseisms. In the sampling procedure, for each instrument, only the average period of the largest well-formed microseisms was usually considered for plotting.

The period characteristics of microseisms seem to depend on the environment of generation and the distance of the generating area. Variations of wind velocity in the generating area have shown no significant effect on microseism period. No period differences attributable to wind strength exist between microseisms generated by cyclonic winds and those generated by much higher velocity hurricane winds. This contradicts the findings of Banerji (1) that period is a function of wind strength.

The depth of water in the generating area seems to be a major factor influencing the periods of microseisms. Although a spectrum of periods actually exists, the dominant period (that with the maximum energy) is a function of the depth of water, increasing as depth increases, and vice versa. Cyclones extending over water expanses of variable depths produce microseism storms with a broad spectrum of periods and exhibiting a characteristic trace irregularity, in contrast to the narrower spectrum and greater regularity of those produced by cyclones over water of more constant depth.

The effect of distance between the generating area and the station seems to be a selective one owing to the more rapid decay of short-period waves during propagation. As a cyclone recedes, the spectrum narrows and is displaced toward longer periods with the record becoming more regular, and with decreasing amplitudes. However, if water depth increases as the cyclone recedes, then as the spectrum narrows, long-period microseisms with higher amplitudes are generated. This indicates an actual increase of energy for the long-period microseisms generated in deep water. Changes in period corresponding to movements of the generating cyclone analagous to those presented above, which are ascribed here to distance-depth factors, have been noted by Bernard (3) and ascribed by him to a Doppler effect resulting from cyclone motion.

The rapidity of the period increase as cyclones emerge from the Grand Banks region around Newfoundland and pass over

deep water seems to preclude the possibility of the production of microseisms by interference of opposing waves or swell as supposed by Deacon (7, 8, 9) and Darbyshire (6), based on theoretical studies by Miche (22), and given further recent theoretical support by Longuet-Higgins (19).

It seems of further significance that once a cyclone has moved over distant, deep water of fairly constant depth, the periods of recorded microseisms reach a maximum and become constant, finally decreasing with decreasing amplitude as the generating area becomes too remote. From a study of microseisms generated by traveling disturbances and recorded simultaneously at many stations, it seems that propagation path does not alter the period of microseisms, which are essentially a function of conditions in the generating area, subject to decay of short-period waves during propagation.

It has been shown here that a study of microseism periods provides a possible means of separating the microseisms produced by more than one cyclone existing in different environments and at different distances. Many instruments tuned sharply to a succession of periods would best accomplish this purpose. A strong indication of possible application to marine meteorology also exists.

Regularity

The correlation of trace regularity to uniformity of depth in the generating area has been referred to above, and in Part I in a rather qualitative manner. A definition of regularity has been given in Part I. The results of a more complete and more quantitative study of regularity is given here since the regularity characteristics seem to be intimately associated with the nature of storm microseisms.

Regular microseisms exhibit the familiar pattern of wave trains or groups of sinusoidal waves which grow to a maximum and then decay, often with rather pronounced quiet intervals between the prominent wave groups. An irregular microseism record is characterized by a more confused-looking trace with waves of obviously different periods and amplitudes and showing little of the symmetrical groups and quiet zones. Individual waves are often very irregular from the superposition of one or more waves upon a larger one of different period and amplitude.

A number of microseism storms exhibiting both regular and irregular characteristics were studied in detail. The periods and amplitudes of one-hundred successive waves with amplitudes above background were measured. Wave period (in tenths sec.) was then plotted against frequency of occurrence of each interval. Six such cases are illustrated here, three from regular and three from irregular microseism storms. Figure 13 (A, B and C) shows three period-distribution graphs from what appeared to be regular microseism storms. The period spectra are relatively narrow, with about fifty percent of the periods occurring within

a range of two-tenths second for cases A and C, and about seventy percent within four-tenths second. The distribution is also fairly symmetrical. Case B shows a slightly wider spread.

These three cases contrast markedly with the period distributions shown in Figure 14 (A, B and C), which are classified as irregular both from the appearance of the original records and from the period-distribution graphs. A relatively broad spectrum of period occurs in each case together with the presence of several modes.

The marine weather responsible for the generation of each of these microseism storms is shown in Figures 15 and 16. Charts A, B and C of Figure 15 show the meteorological storms associated with the microseism storms depicted on graphs A, B and C respectively of Figure 13. Microseism Storm A (Palisades) was generated by a deep cyclone centered between southern Greenland and Labrador over deep ocean waters. The period peak at 5.5 seconds is comparable to the average period noted for such distant deep-water cyclones discussed in the section on case histories.

Case B (Palisades) refers to the microseism storm generated by the cold front off Long Island (Chart B, Figure 15). The narrow period spectrum peaked between 3.0 and 3.5 seconds corresponds very well with the average of measured periods for the response of this instrument to cold fronts (see Part I). The water depth on the continental shelf beneath the generating section of the narrow front can be considered quite uniform.

Case C was a microseism storm generated by the hurricane shown on Chart C (Figure 15) and recorded at the U.S. Navy Hurricane Tracking Station on Bermuda. The regular microseism storm is here associated with a storm over very uniformly deep water.

The irregular microseism storms shown on graphs A, B and C of Figure 14 were generated by the meteorological disturbances shown on Charts A, B, and C respectively of Figure 16. Cases A (Weston) and C (Palisades) were generated by two intense cyclones centered near the edge of the continental shelf, and extending continuously from land to deep water. Case B (Weston) is an irregular storm associated with the strong northerly flow of cold air over a large area of ocean water of very variable depth.

Effects similar to the above have been described by Gherzi (14) in 1932, in which monsoon winds over a large area resulted in irregular microseisms, whereas microseisms of cyclonic generation showed the familiar group pattern.

The above data and correlations strengthen the conclusion that the period of microseisms is a function of depth in the generating area and that regular microseism storms are generated by marine storms over water of uniform depths, while irregular microseisms are produced by marine storms over water of variable depths as indicated by the broad spectrum of periods generated. It should be noted that regularity must be considered in terms of degree of flatness of instrumental response. With experience an observer can estimate many parameters of marine storms from the appearance of microseism records.

Notes on Nature and Origin of Microseisms

Microseism records exhibiting clean, symmetrical wave groups with quiet intervals only occur for storms that have relatively narrow period spectra. The interference of two trains of microseisms of slightly different period could produce the "beats" common to regular records. The lack of beat patterns on irregular records is explainable by the interference of microseisms of very diverse periods and amplitudes.

One further situation is considered here. Figure 17 shows the record of the microseism storm commencing about 00 00 of November 26, 1949, as recorded by the long-period Palisades seismograph. The period distribution for one-hundred waves is shown in Figure 18. The spectrum is very narrow with forty-one percent of the waves having a one-second spread, and seventy-two percent having a four-second spread. From the above study, this would indicate a meteorological disturbance over uniform and rather shallow depths (considering the value of the period), and fairly close to the station.

Figure 19, A through D, shows four weather charts at six-hourly intervals for November 25-26, 1949. It is seen that Chart C illustrates the marine weather at just about the onset of the microseism storm. Despite the strong winds (force 6) prevailing over offshore waters during the times of Charts A and B, no microseisms attributable to these winds occurred. It was not until the low-pressure center and the cold air with winds of only force 3 to 4 passed near the station that the microseism storm commenced. It then intensified as the wind

velocity in the cold air increased to force 6 (Chart D). This lack of microseism generation by a stream of warm air has been noted earlier in Part I. On the other hand, the cold northerly stream of air covering the same water area, shown in Figure 16, B, resulted in a definite microseism storm.

It seems significant that the strong southerly air flow shown in this case would be most conducive for the development of reflected waves from the rocky New England coastal areas which could interfere with incoming waves or swell thereby becoming a mechanism in microseism generation. Further, the strong southerly winds are those most conducive for the generation of high surf on the southern New England and Long Island shores, but again no microseisms attributable to this effect are noted. However, northerly and northwesterly or westerly winds, such as those referred to above, which are least likely to produce either reflected waves of the appropriate period, or surf in this area result in most pronounced microseism storms.

In this connection, one last and noteworthy case is given now. Figure 20 illustrates the striking onset of the microseism storm of Feb. 7-8, 1951, as recorded at Palisades, N.Y. by a short- and long-period seismograph. The associated weather conditions appear on Figure 21.

Preceding the abrupt commencement of the microseism storm, the trace, prior to 2200, Feb. 7, is contrastingly quiet. Nevertheless, weather charts A and B (1230 and 1830, Feb. 7) indicate the existence, during the quiet microseism interval, of winds with velocities up to force 8 in a strong southerly air

stream offshore. Based on the isobar spacing, computed surface velocities are much higher. By interpolating coastal weather conditions between the times of charts B and C, it can be seen that the abrupt and rapid increase in microseism intensity, about 2200, corresponds to the passage of the leading edge of cold northwesterly air from the coast onto the sea.

Phenomena almost identical with the above situation, and others similar to it given earlier have been described by Jones (17, 18) for the Southern Hemisphere, in which microseism storms commenced with the passage from land to sea of southerly air masses.

All of the information given above tends to minimize the importance of standing waves produced by swell, progressive swell in shallow water, or coastal surf as factors in the generation of the microseisms studied here. The empirical evidence also suggests that friction from the action of wind over water is less significant in microseism generation than the pulsational effect associated with turbulence inwinds of high velocity or with unstable conditions in cold air or cold fronts.

SUMMARY OF CONCLUSIONS

1. Microseism storms are generated at sea beneath atmospheric disturbances, the most intense storms resulting from large area cyclones of high wind velocity. Cold fronts produce less intense microseism storms of shorter duration.

2. The amplitudes or intensity of recorded microseisms are a function of several meteorological and environmental parameters associated with the atmospheric disturbances, as well as the distances of the disturbances from the station and the nature of the recording instruments.

3. The period-spectrum of the microseisms generated appears to be a function of the depth of water in the generating area - the greater the depth, the higher the period.

4. The spectrum of periods recorded at a given station is a function of both the depth of environment beneath the disturbance and the distance of the disturbance, since short-period microseisms decay more rapidly during propagation.

5. The regularity of recorded microseisms appears to depend principally upon the uniformity of water depth in the generating area, which further supports the thesis that the period generated is a function of water depth.

6. The position and nature of the generating cyclones can often be estimated from the period and regularity characteristics of recorded microseisms. Cyclones in different positions or at different distances existing simultaneously can often be distinguished in this way. A battery of sharply tuned seismographs should prove valuable for this purpose.

7. Linear surface streams of cold air are much more efficient mechanisms in the production of microseisms than streams of warm air of greater dimensions and velocities. It has been shown previously that cold fronts are similarly more effective than warm fronts in microseism generation. This all suggests that the mechanism of microseism origin lies in a pulsational effect in the atmosphere possibly produced as a result of instability and turbulence in cold air, and from turbulence only in the case of warm air moving at very high velocities, i.e., hurricanes.

8. All the evidence from the cases studied and those presented here tends to strongly oppose the importance of coastal surf, and progressive or standing waves or swell as being mechanisms in the generation of the microseisms studied in this work.

9. A strong indication exists that microseism energy is dissipated by either the relatively steep seaward face of at least a portion of the east-coast continental shelf, or by a discontinuity in the basement in the same area.

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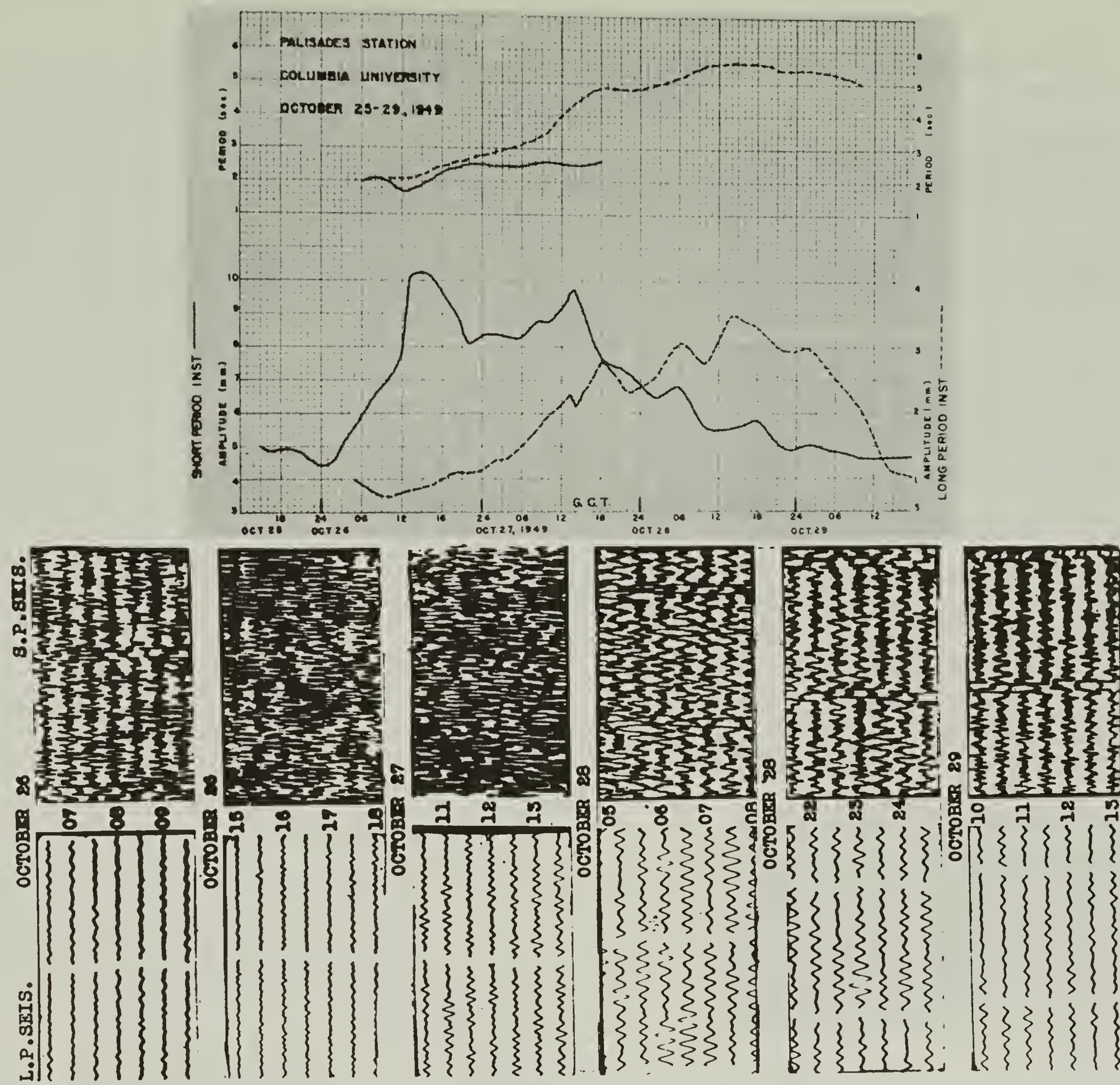

Figure 1. Graph of microseism trace amplitudes and periods and portions of seismograms for Palisades for October 25-29, 1949.

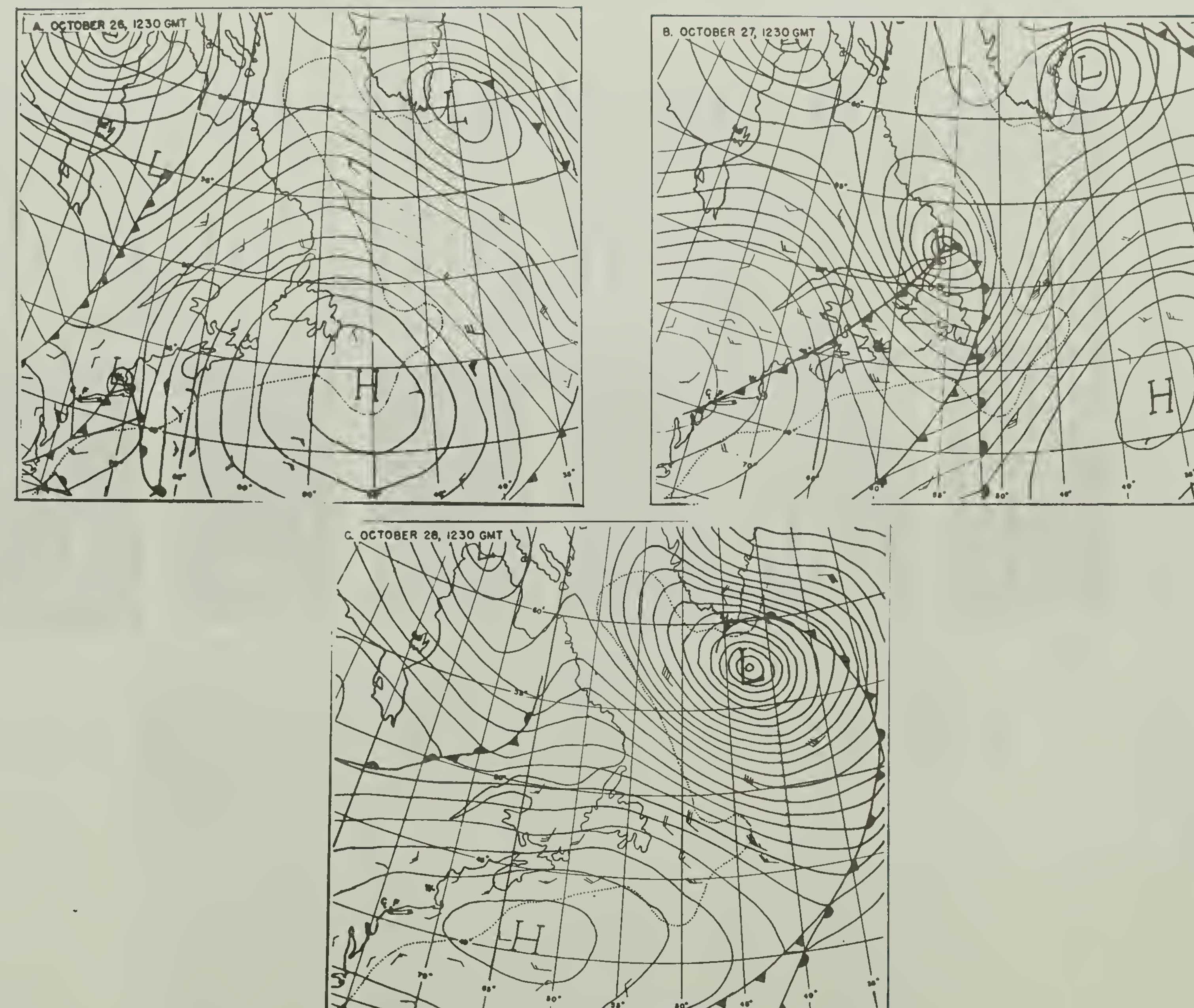

Figure 2. Weather charts of the eastern North Atlantic for October 26-28, 1949.

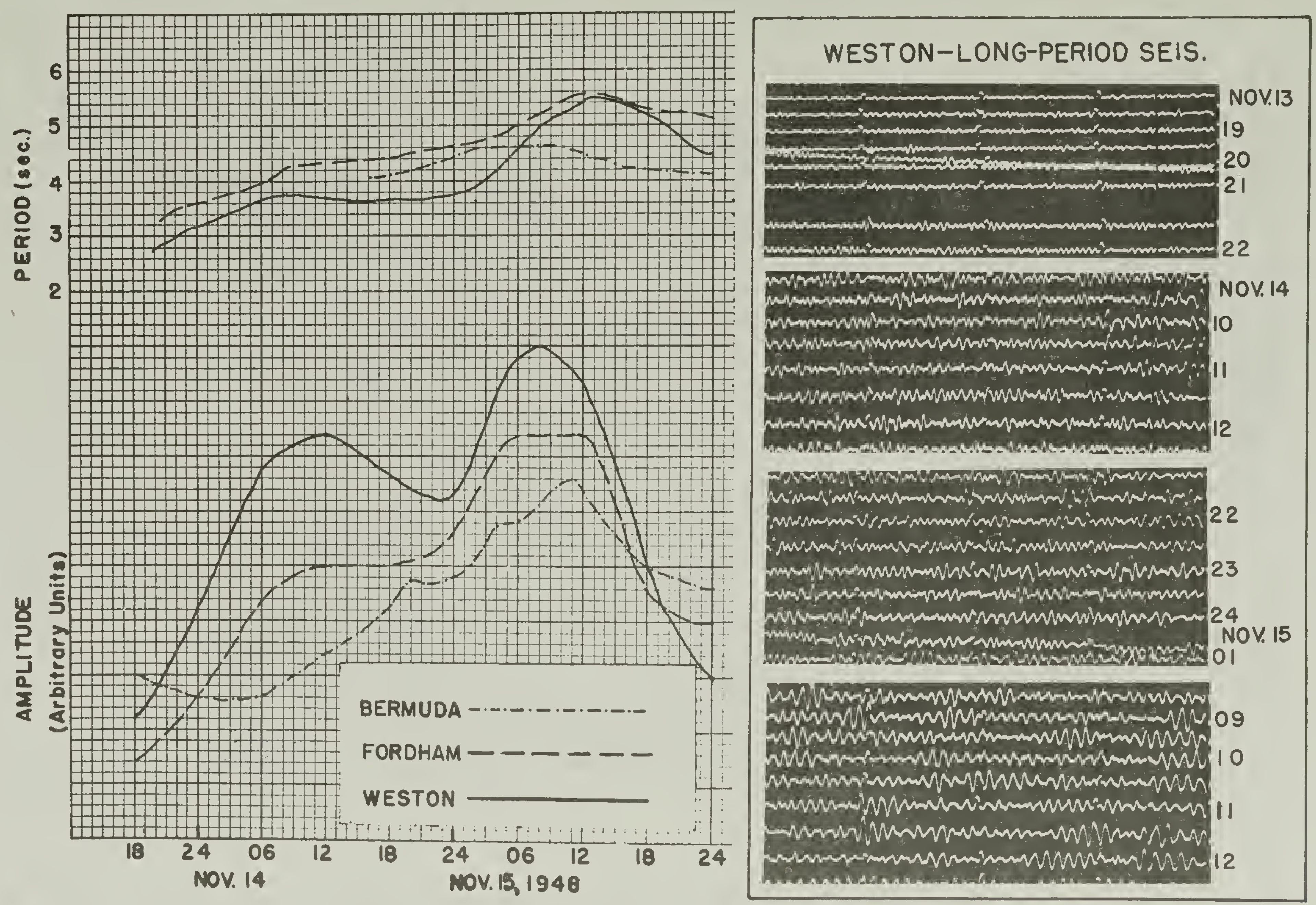

Figure 3. Graph of microseism trace amplitudes and periods for Bermuda, Fordham and Weston, and portions of the Weston seismograms for November 14-15, 1948.

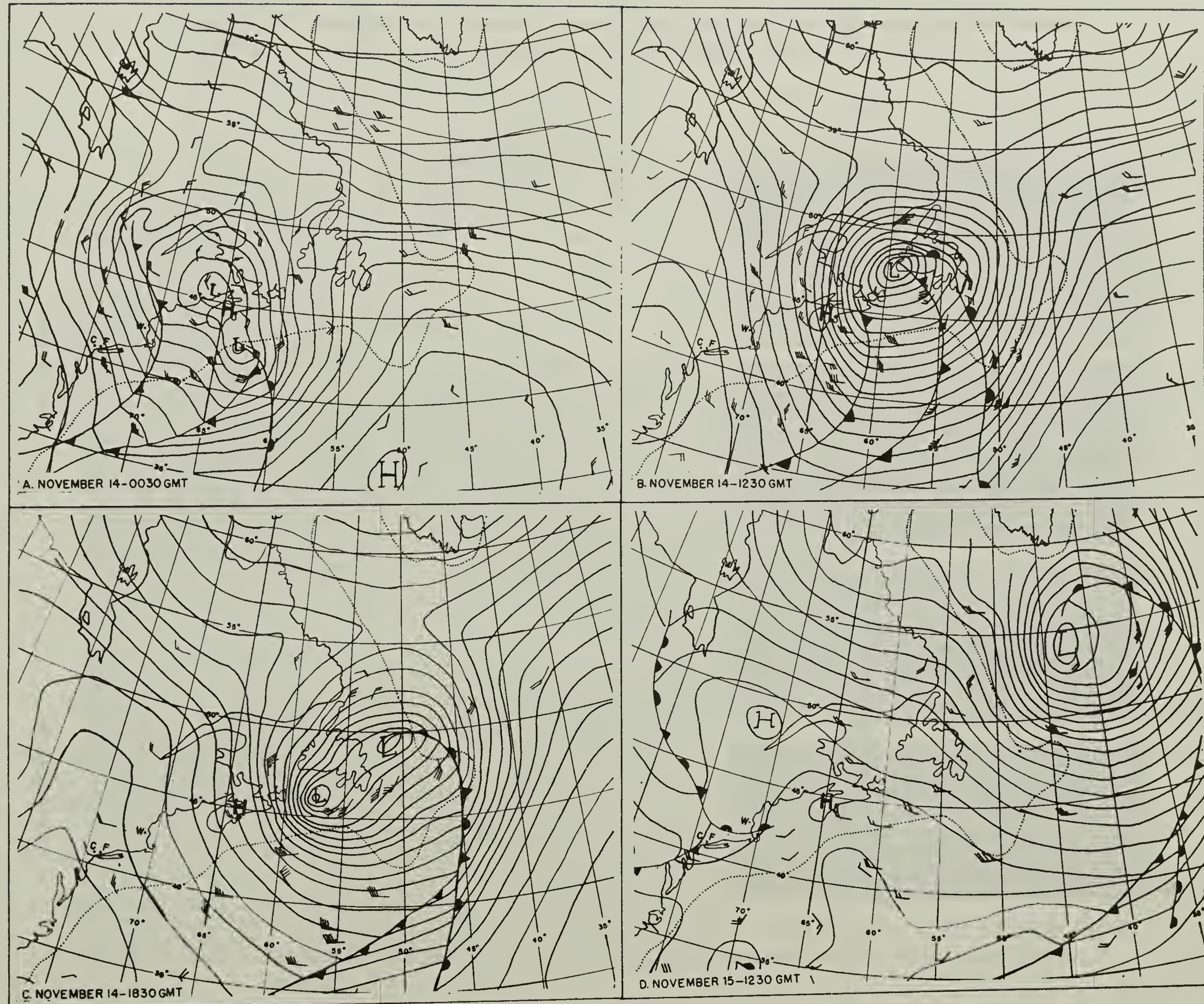

Figure 4. Weather charts for November 14-15, 1948.

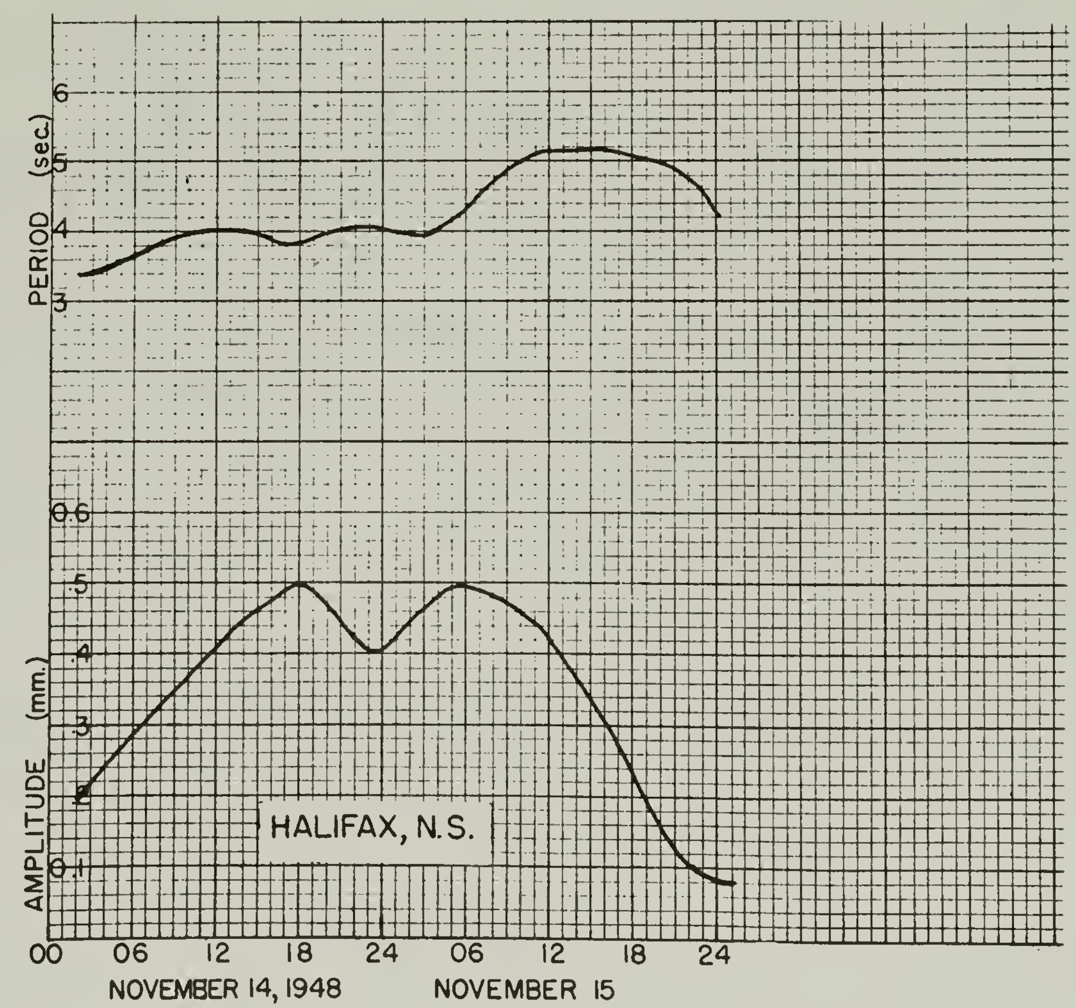

Figure 5. Trace amplitudes and periods for Halifax for November 14-15, 1948.

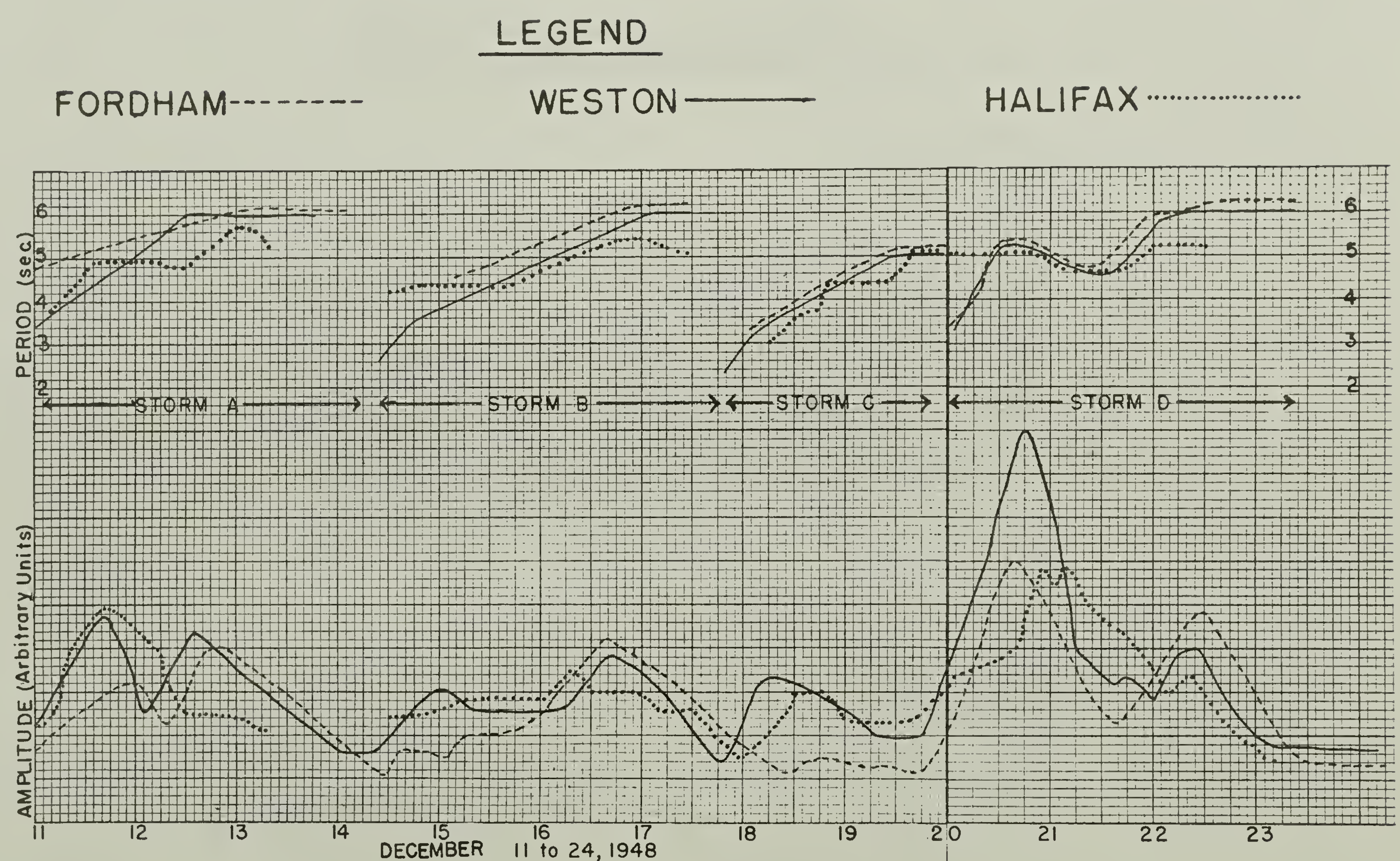

Figure 6. Graph of trace amplitudes and periods of four microseism storms as recorded at Fordham, Weston and Halifax. (The amplitude scale for storm "D" for each of the curves has been reduced one-half relative to the scale for the preceding storms).

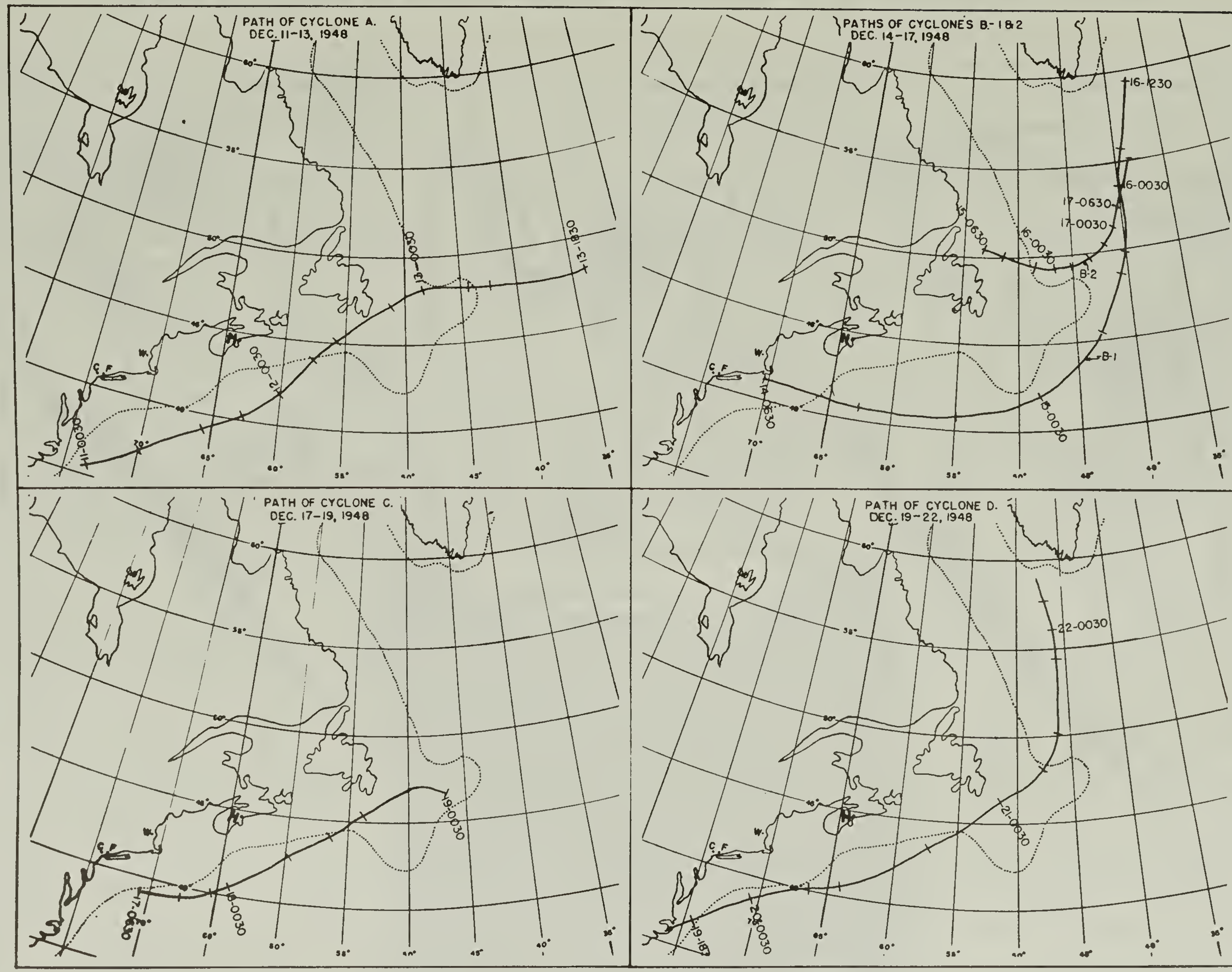

Figure 7. Charts showing the paths of cyclone centers during December 11-24, 1948.

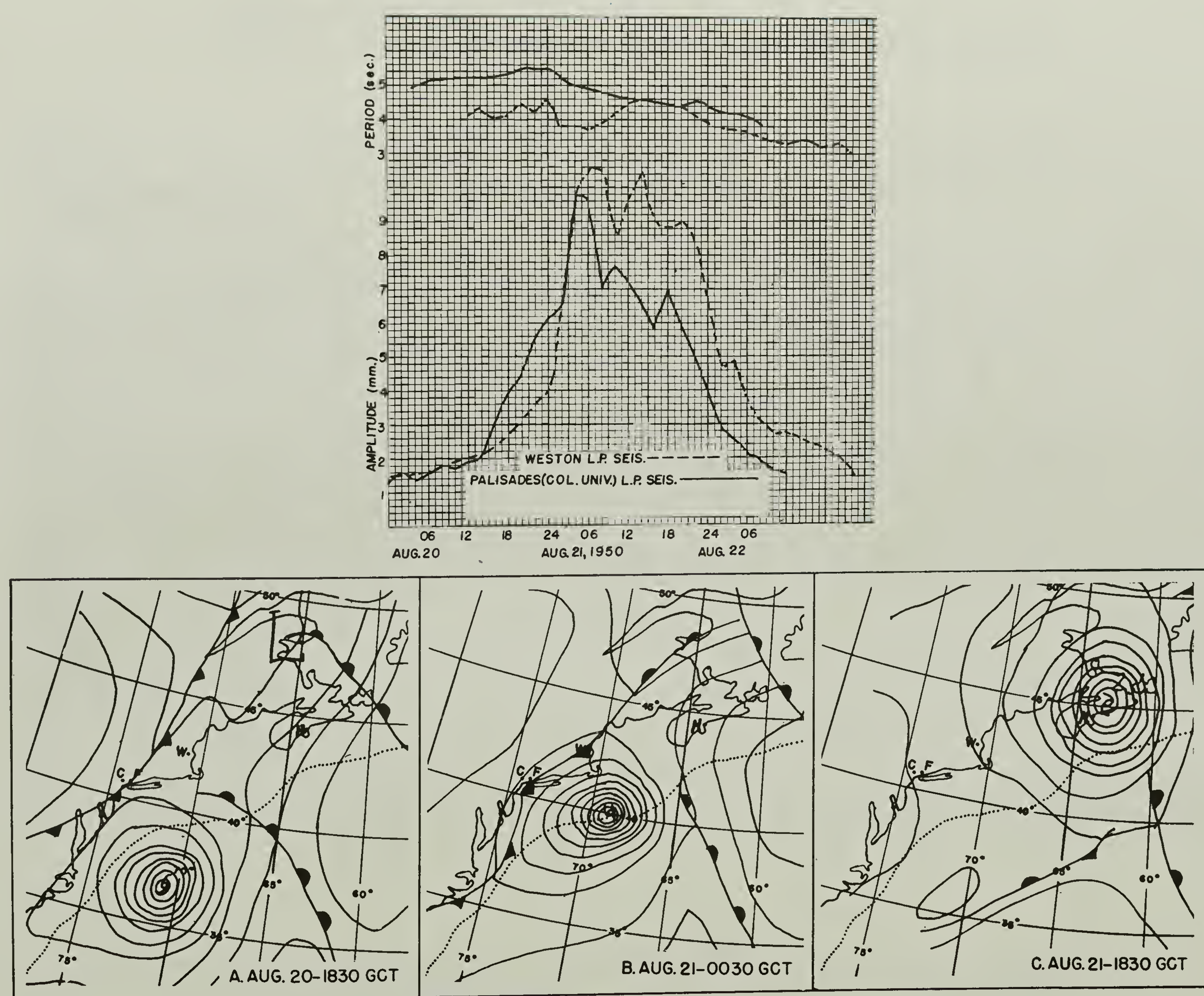

Figure 8. Graph of trace amplitudes and periods for hurricane microseisms recorded at Weston and Palisades during August 20-22, 1950, and weather charts of the hurricane.

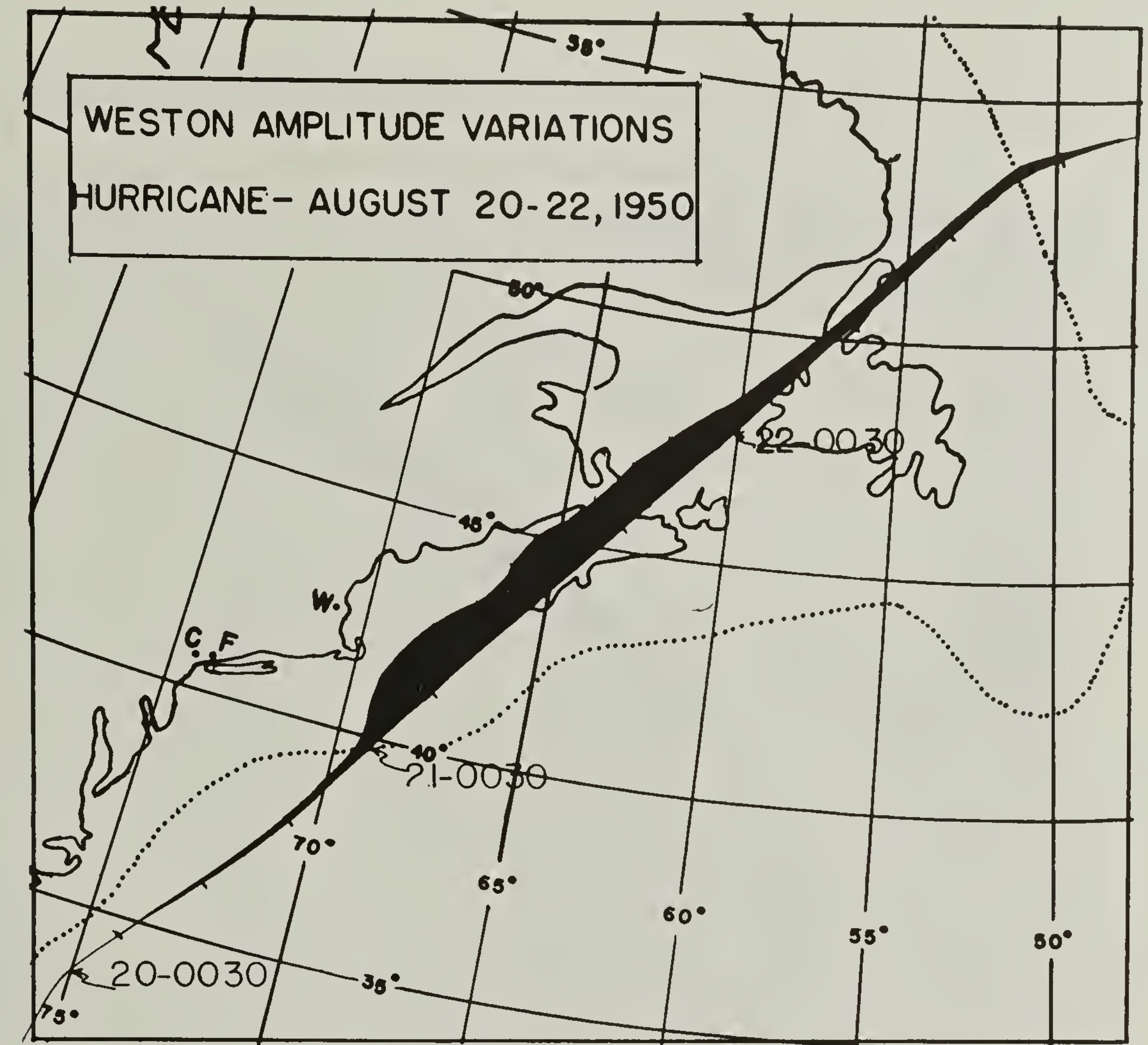

Figure 9.

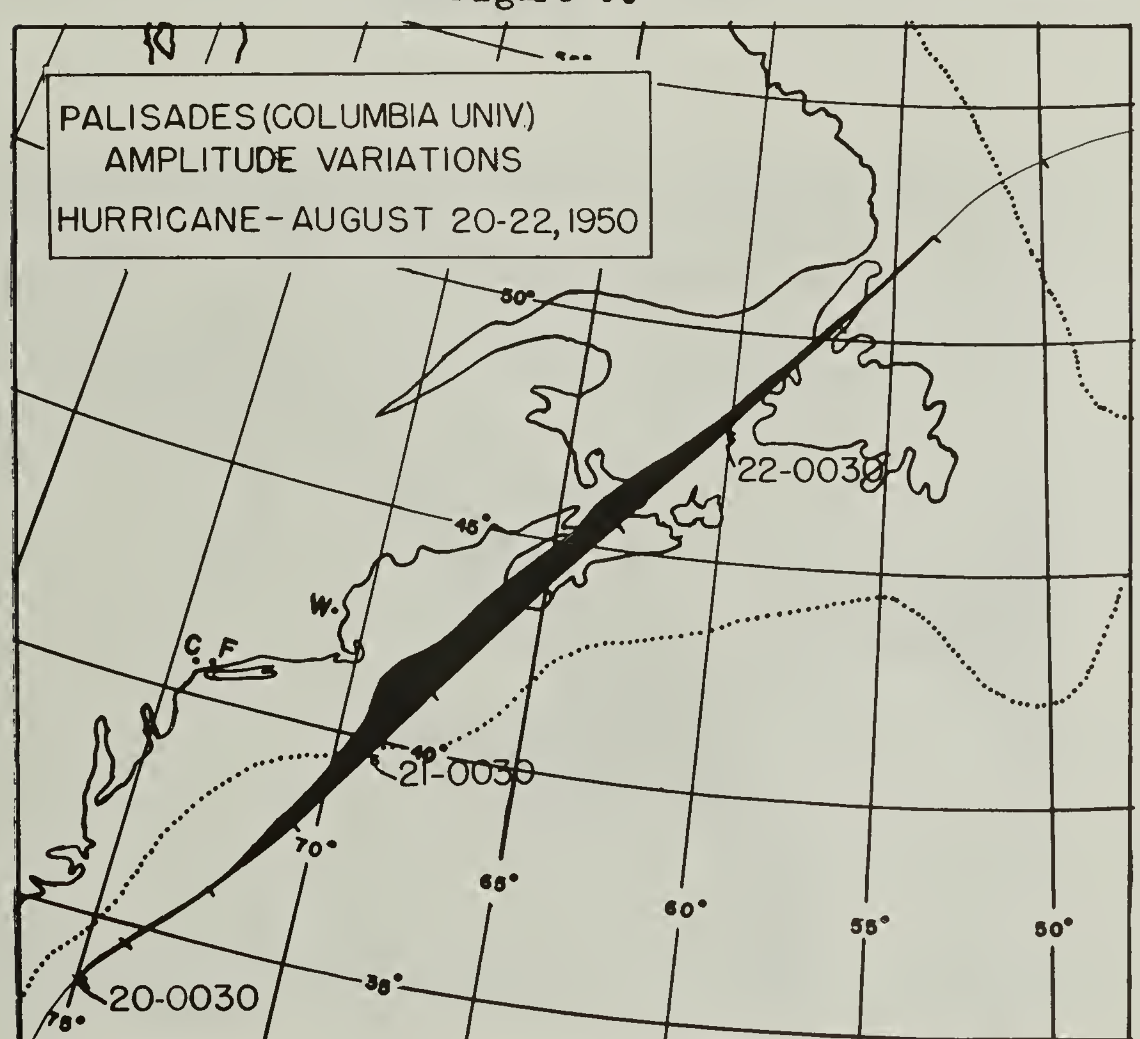

Figure 10.

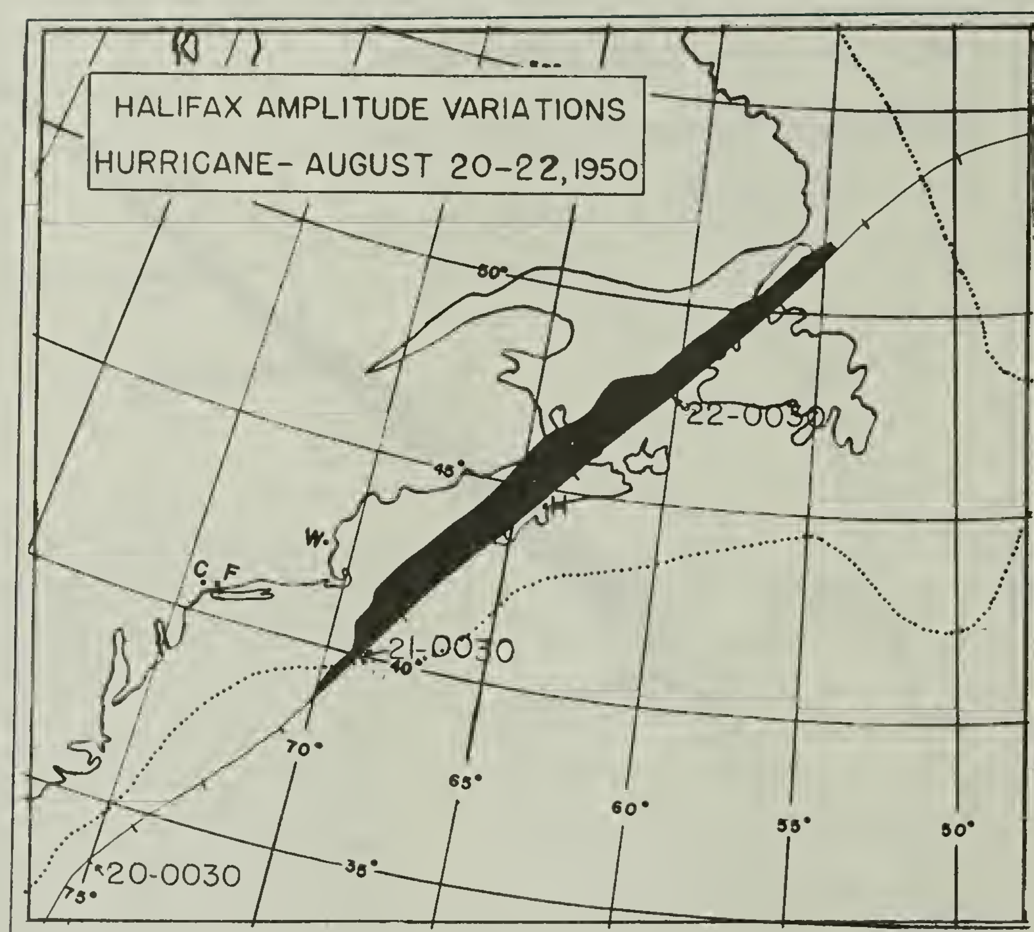

Figure 11.

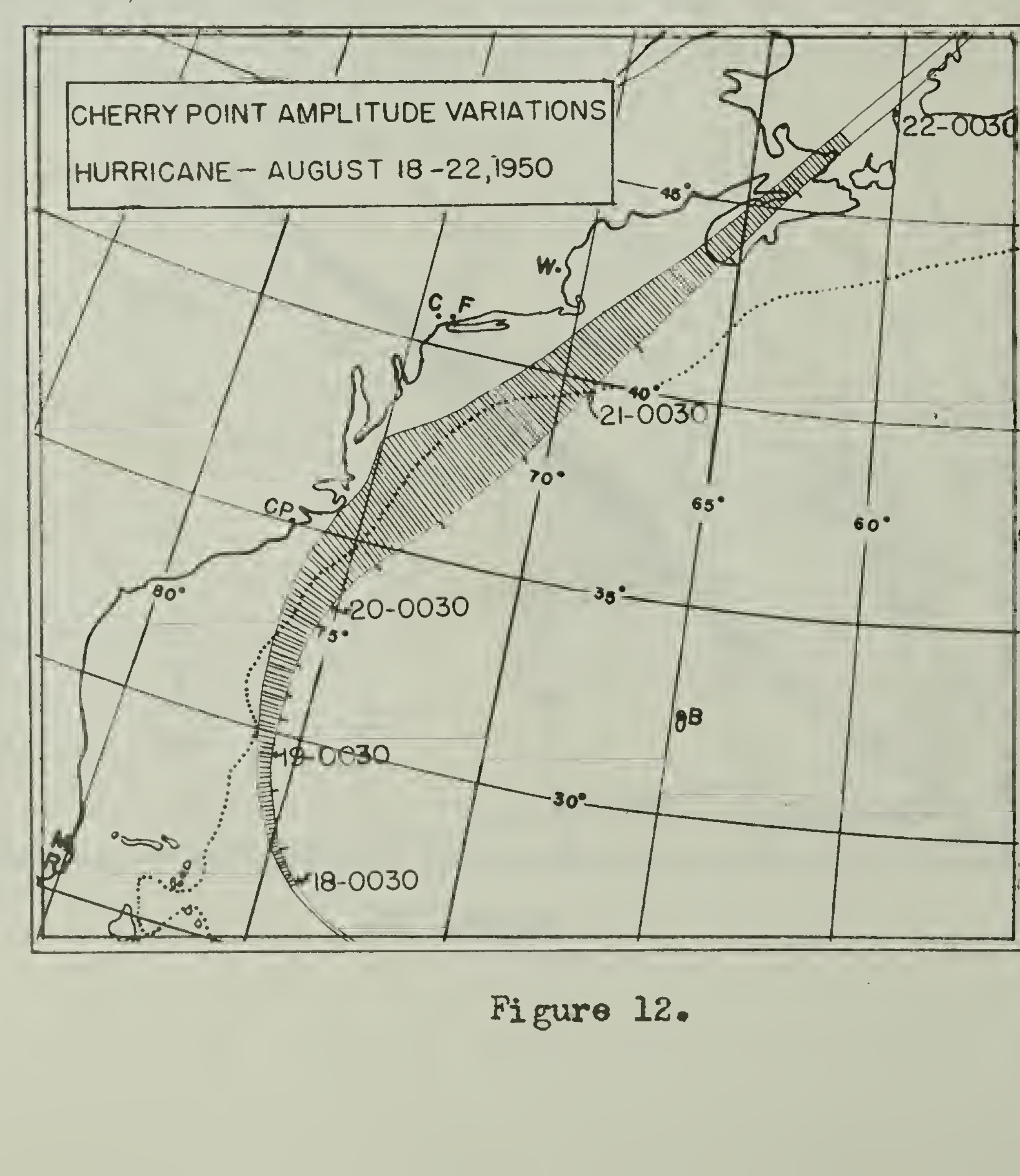

Figure 12.

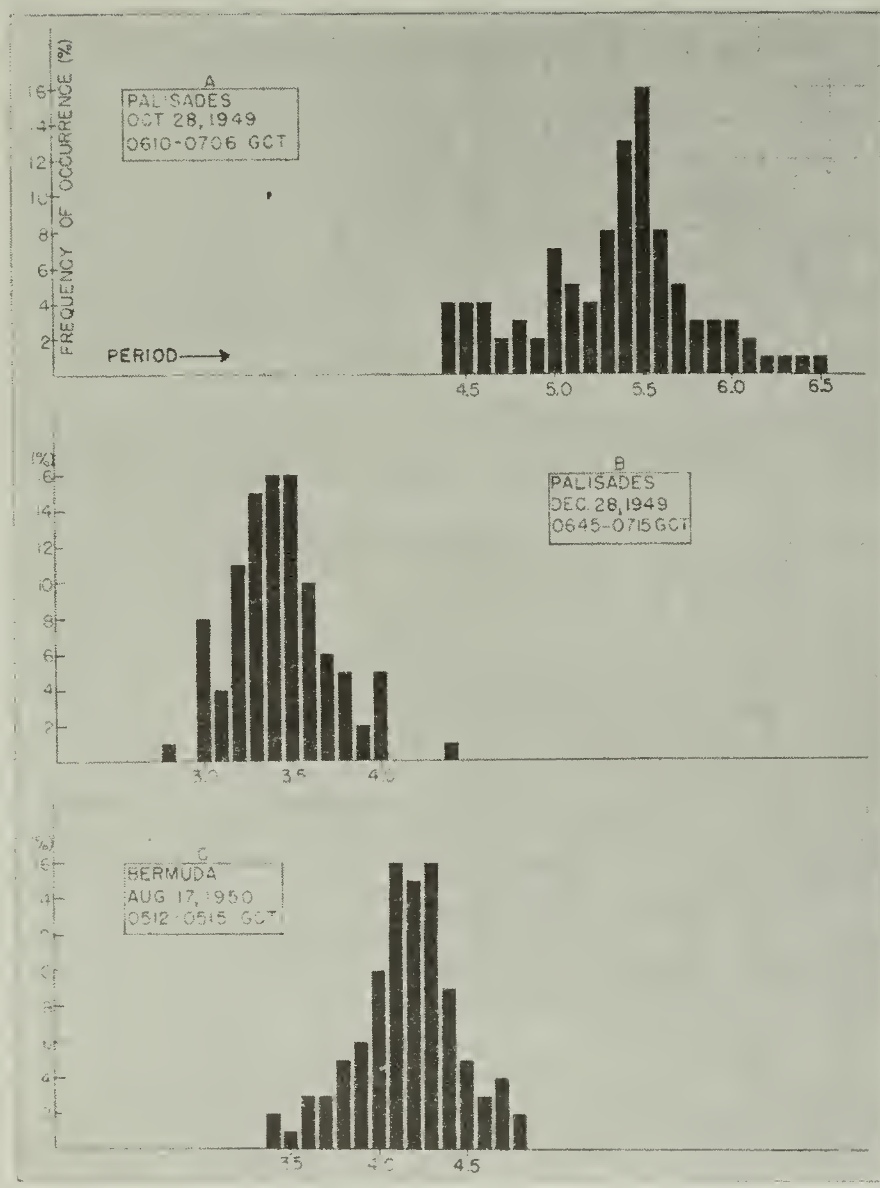

Figure 13. Graphs showing period distribution for three "regular" microseism storms.

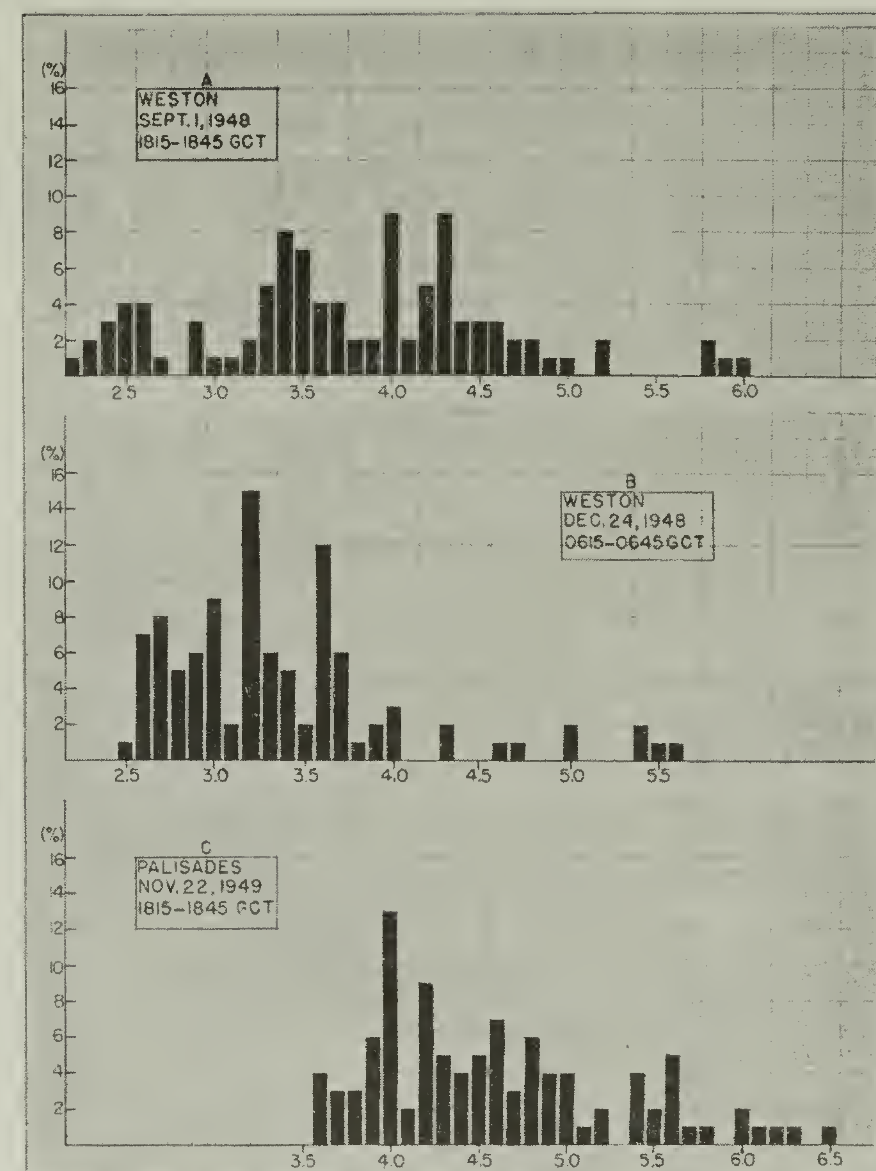

Figure 14. Graphs showing period distribution for three "irregular" storms.

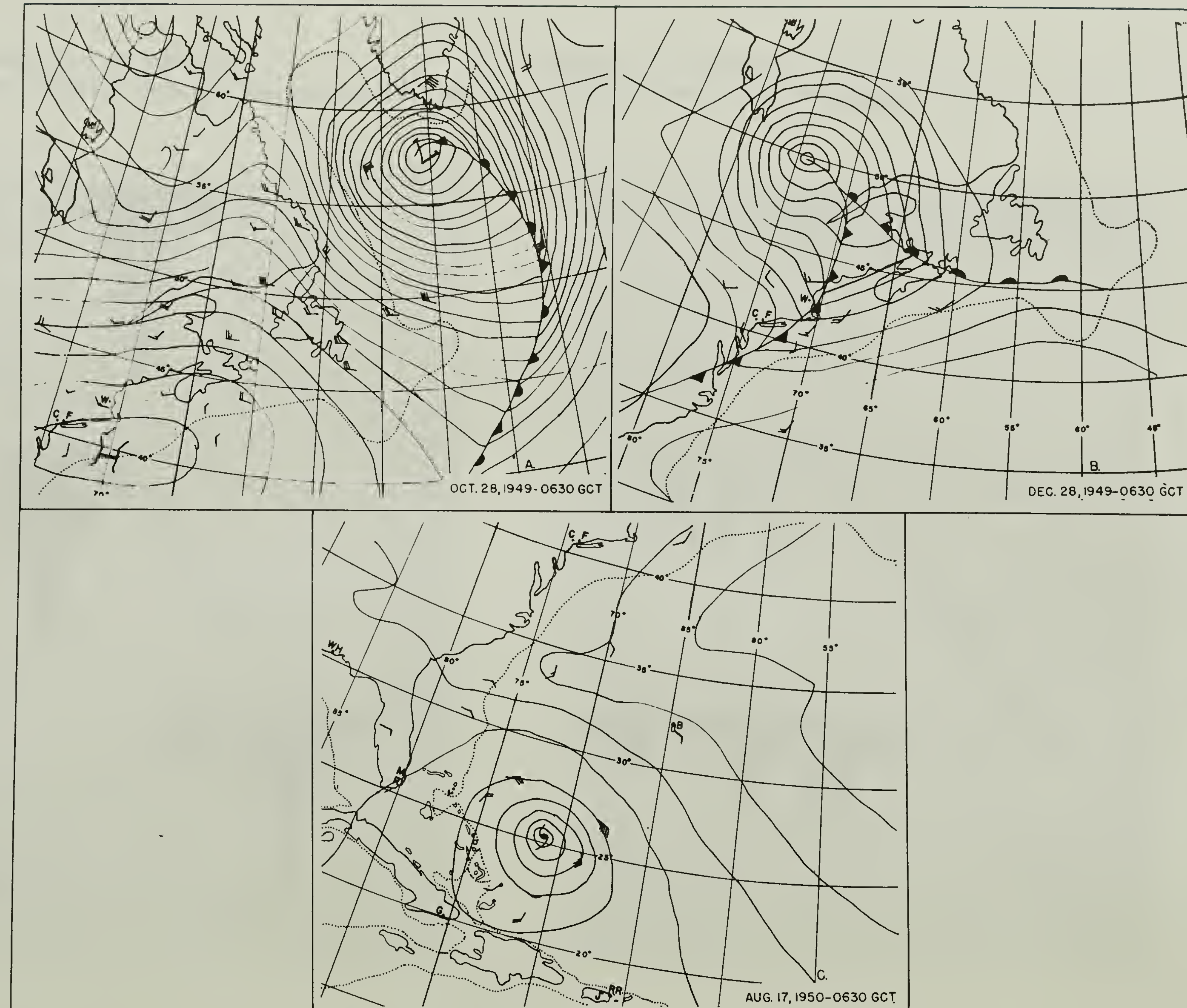

Figure 15. Weather charts showing marine atmospheric storms responsible for the microseism storms illustrated in Figure 13.

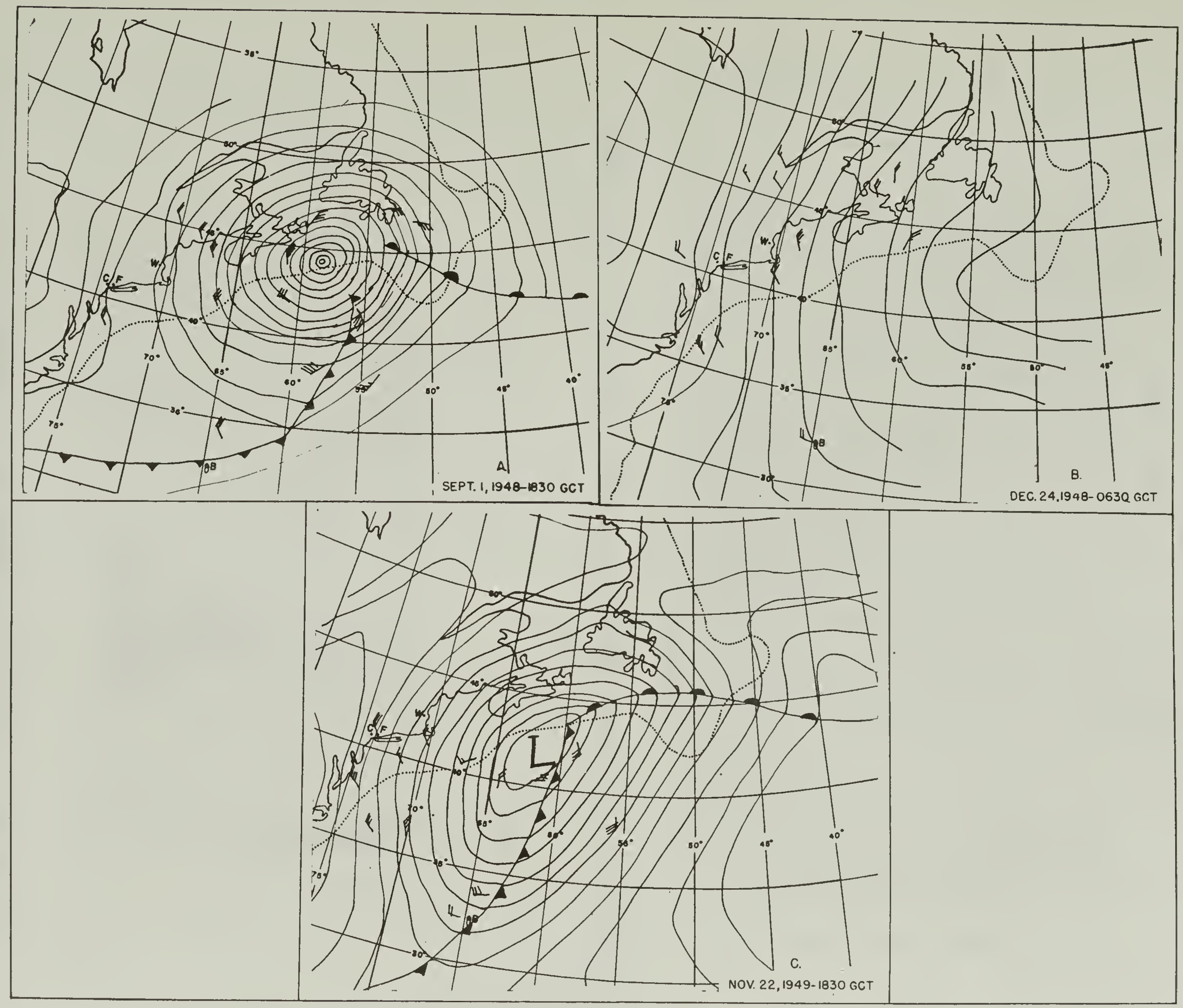

Figure 16. Weather charts showing marine atmospheric storms responsible for the microseism storms illustrated in Figure 14.

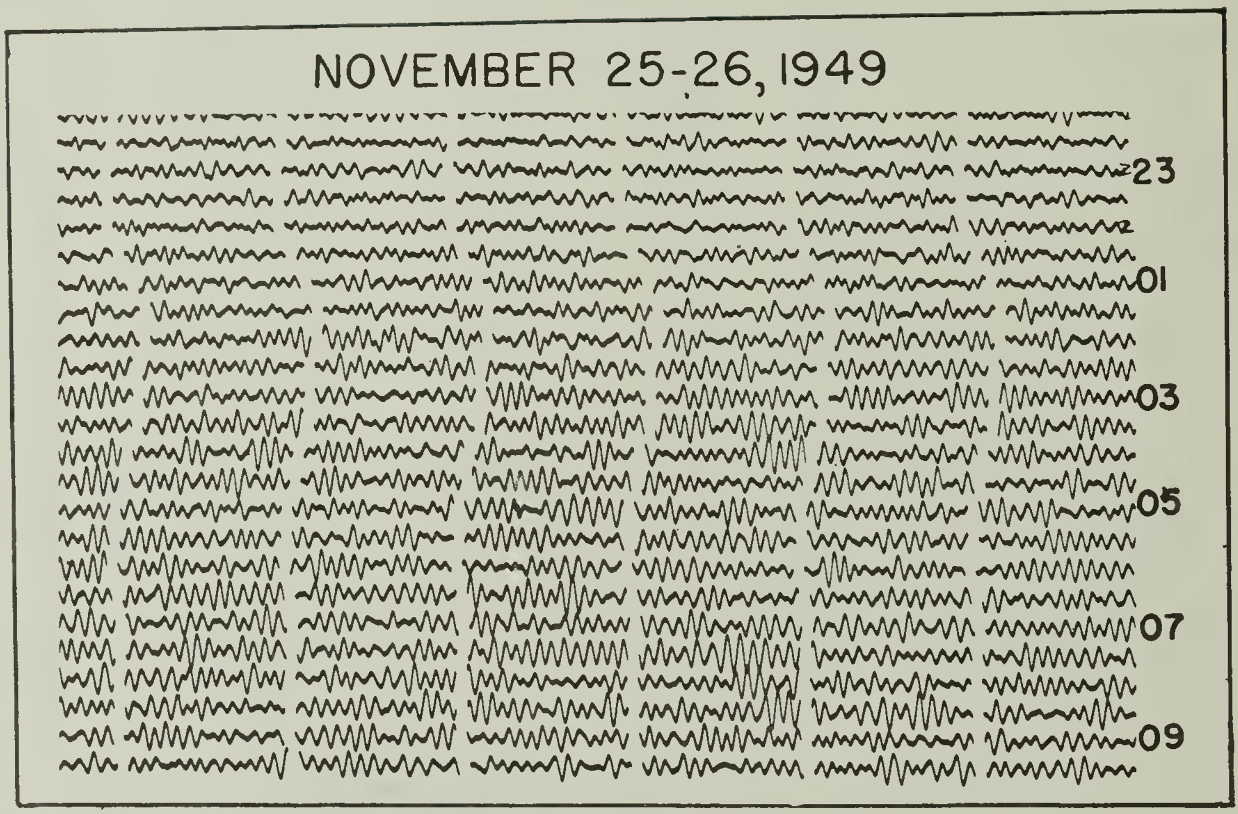

Figure 17. A portion of the Palisades long-period seismogram.

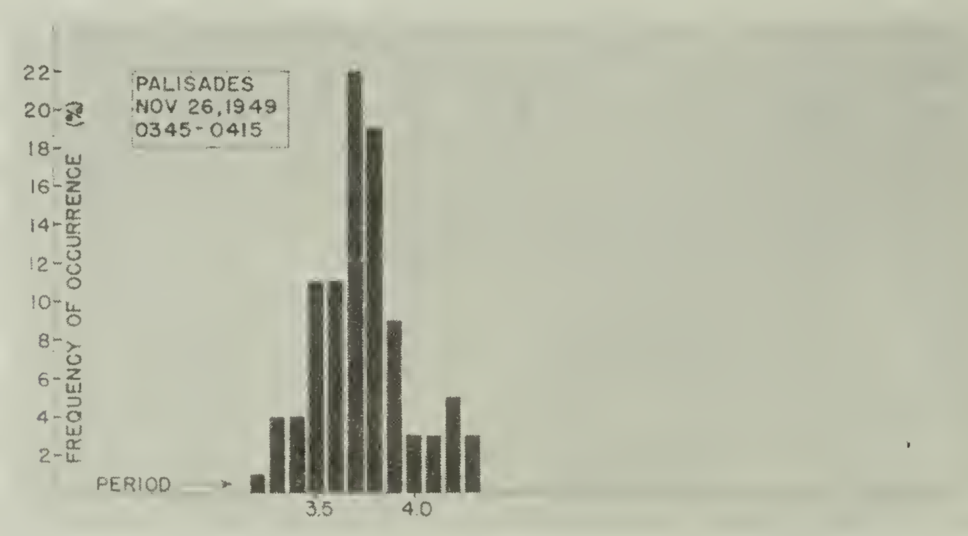

Figure 18. Period distribution for microseism storm of November 26, 1949, as recorded at Palisades.

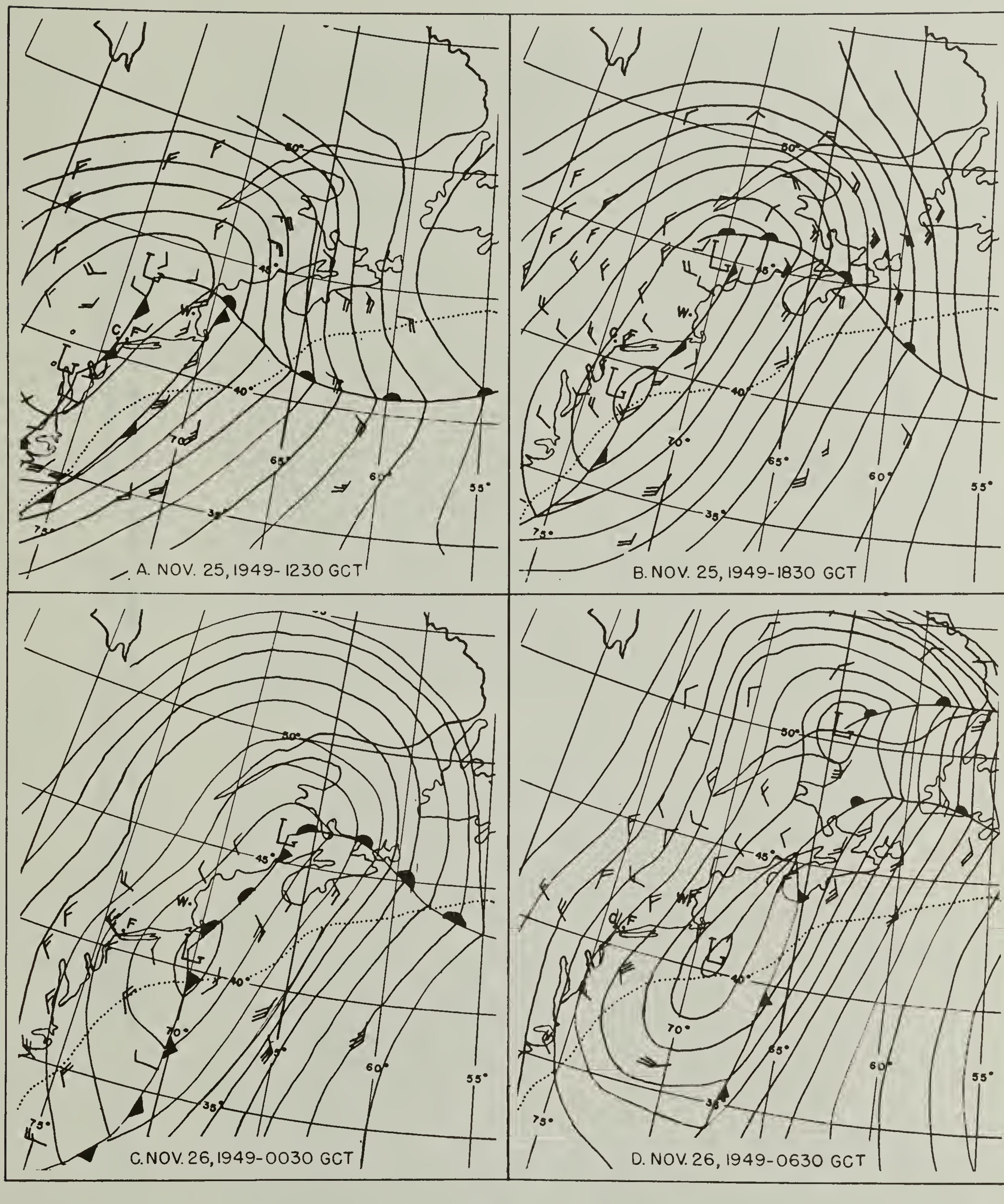

Figure 19. Weather charts illustrating cyclone of November 25-26, 1949.

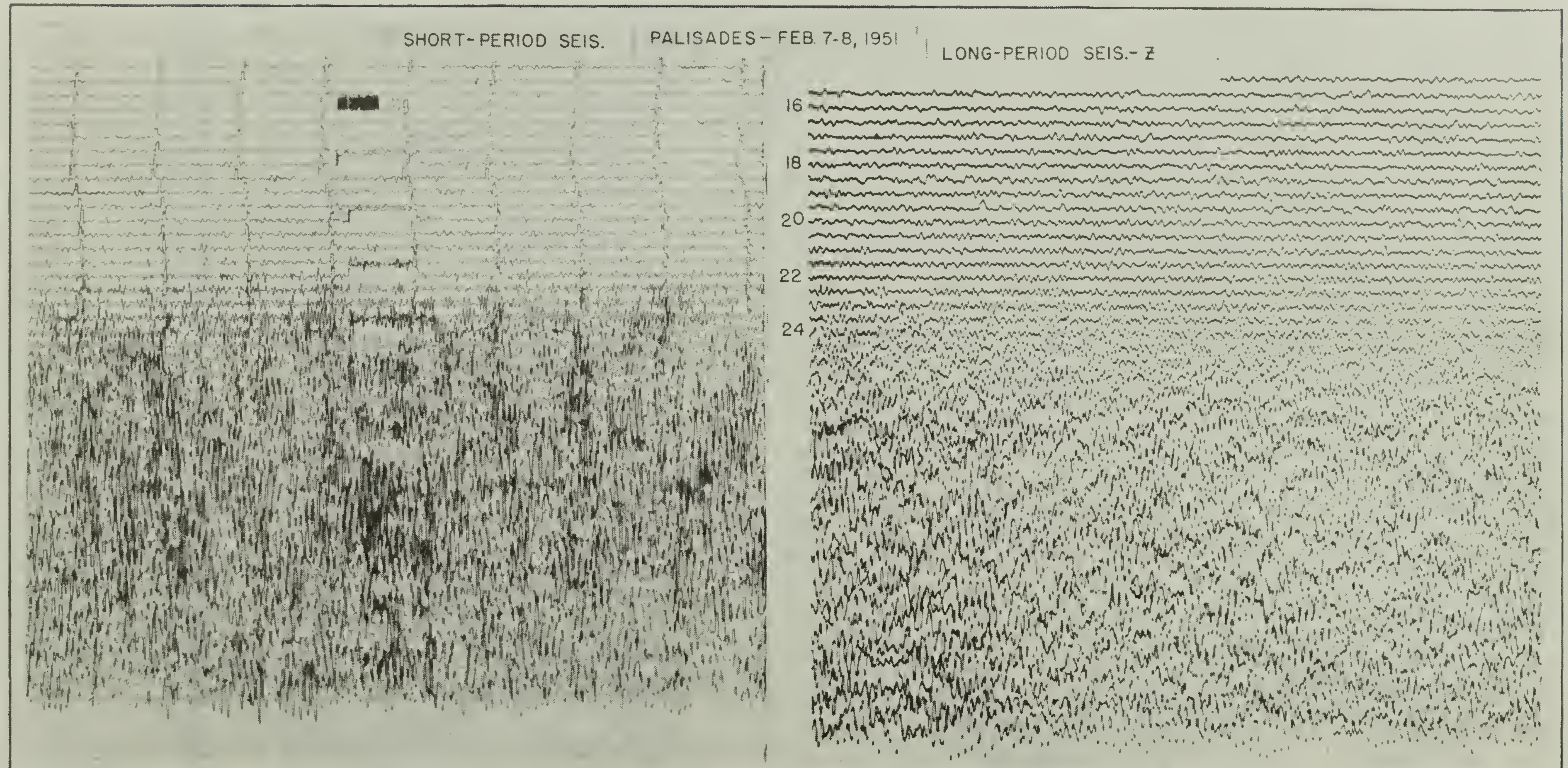

Figure 20. Seismograms illustrating the quiet conditions preceding, and the abrupt beginning of the microseism storm of February 7-8, 1951.

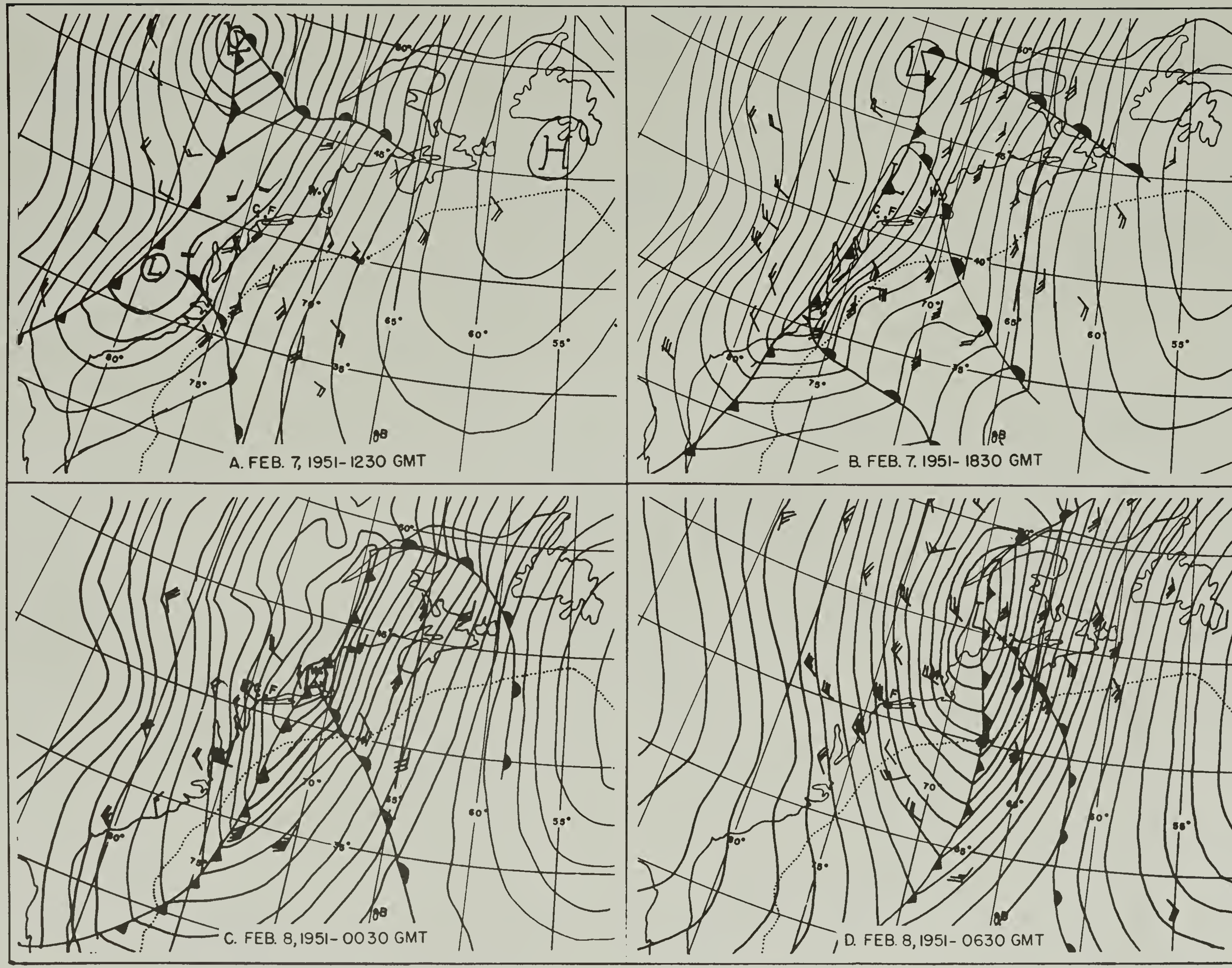

Figure 21. Weather charts of cyclone of February 7-8, 1951.